The Brain's Dynamic Way of Keeping in Touch

In the monkey, brain pathways for registering sensations of touch are not hard wired but remain unexpectedly fluid in adulthood

"The dominant view of the nervous system is of a machine with static properties. Our work shows this general view to be incorrect. The machine has embedded processes that make it self-organizing and that are driven by experience throughout life," says Michael Merzenich, director of the Coleman Laboratory of the University of California at San Francisco.

Merzenich's assertion, which has broad implications for the understanding of brain function and the brain's ability to recover from injury, is based on studies of monkeys he and his colleagues have conducted.* The researchers find that certain sensory pathways in the brains of monkeys remain functionally fluid throughout adulthood: the internal relationships of "maps" representing sensory inputs within the brain are not anatomically frozen, as was previously thought.

To be sure, notions about how plastic the central nervous system of higher mammals is in adulthood have been in considerable flux during the past few years. There is a growing belief among scientists that many physical and functional injuries in the brain, once thought irreparable, might instead be correctable to some extent. The process of learning, also, is a demonstration of long-lived plasticity in the brain.

Nonetheless, Merzenich's findings challenge a prevailing notion that most sensory pathways in the nervous system are "fixed" or "hard wired" by the maturation of anatomic connections, either just before or soon after birth. They also address the puzzling question of what forces may be at work when stroke victims partly recover. Do "redundant copies" of skills exist outside the damaged regions, or is physical damage within the brain repaired over time? Or can old skills be newly established in different, undamaged brain regions?

Moreover, Merzenich's findings are being applied to support a theory of brain function that has been developed by Gerald Edelman at Rockefeller University and his collaborators. Edelman argues that a process of natural selection works within the brain. The process, which continues throughout adulthood, is essentially a "Darwinian competition," he says, that involves "staggering dynamics." Edelman, Merzenich, and their colleagues have collaborated since 1982 under the auspices of the Neurosciences Institute in New York.

The primary experimental focus of Merzenich's research has been a region of the cerebral cortex where certain sensory impulses are registered. Typically, the experiments have entailed mapping the cerebral locations where touch sensations from the fingers and hands of adult squirrel and owl monkeys are represented. This involves taking detailed physiological measurements using microelectrodes inserted in the animals' brains and then producing electrophysiological maps of that brain region. Some of the findings, based on studying the somatosensory system, recently have been extended to the auditory system.

> Merzenich infers that the activity of any single nerve cell is trivial. What is crucial is a nerve's role in a network. . . .

Each animal that the researchers have studied organizes its touch information onto a topographically unique space in the cortex. From one animal to the next, the maps of such spaces differ idiosyncratically in size and in other details, although they share many general characteristics. For example, in any particular monkey, the map in the brain that corresponds to touch sensation in the hand can be subdivided into regions for each of the animal's five digits and for other surfaces of the hand.

Merzenich's unexpected finding is that this pattern is not static. Instead, it can move and change shape spontaneously or in response to experience. Merzenich and his colleagues are determining the rules by which these nervous system representations rearrange. "The first rule is that reorganization always occurs with maintenance of neighborhood relationships," Merzenich says. Thus, the brain's representation of touch sensations along a monkey's fingertip may move within a zone that is roughly 1200 micrometers in diameter but, as it does so, the relations of its component parts remain constant.

These rules were detected by observing the way the brain maps shift after one or more of an animal's fingers is amputated. The researchers first determine the pattern of signals in the brain that results when an animal's fingers are touched. Then, for example, the middle finger is removed, and the changes in the signal patterns are observed.

Those changes are orderly and characteristic. Sensory inputs from the remaining, adjacent fingers progressively shift into the missing finger's hitherto exclusive brain region. This expansion of inputs from fingers 2 and 4 into the adjacent brain zone is gradual but steady over the course of several weeks, Merzenich finds.

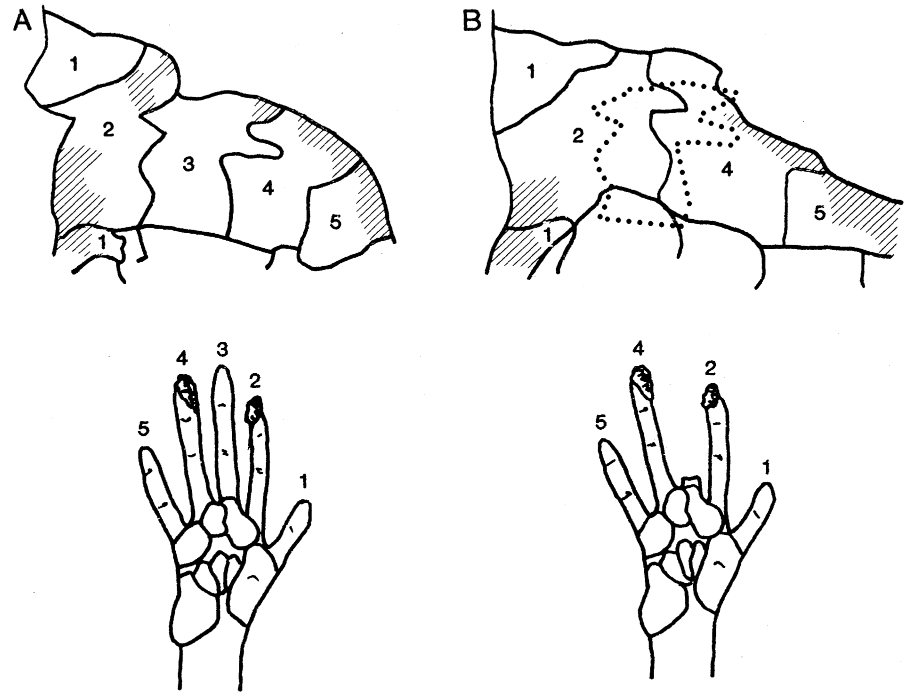
When the shift is complete, the brain regions representing the still-intact surfaces of the hand are considerably expanded, making the representations of the two fingers finer grained than they were before the finger between them was removed. In other words, the details of the animal's touch maps are improved substantially for its remaining fingers. A similar increase in acuity has been noted in human patients who undergo amputation.

This dynamism within the brain also is seen at work when the physical change originates there rather than at the periphery. For example, if a portion of the cerebral cortex is injured, the appropriate somatosensory map can move to the region surrounding it, albeit with some loss in acuity compared to beforehand. This movement of the map is believed not to involve cell growth or movement, but instead to depend on a spatial shift of nerve cell activity, as detected by microelectrode probes. Once again, the overall shift is confined to an area with a diameter of roughly 1200 micrometers.

Another important aspect of sensory maps in the brain is that they are self-organizing. Merzenich believes that straightforward temporal correlations among neural inputs may be the crucial force underlying this self-organizing

---

*Merzenich's colleagues at the University of California include Michael Stryker, William Jenkins, Mriganka Sur, Randall Nelson, John Wall, and John Zook. The research has involved a close collaboration with Jon Kaas and his colleagues at Vanderbilt University.



Brain maps of monkey hand surface representations

Microelectrode analysis of the appropriate area in the cortex of adult owl monkeys shows a distinct and orderly shift in the way the tactile inputs are represented. The area representing digit 3 before it is amputated (A) is fully partitioned by areas representing the two adjacent digits several weeks after the operation (B).

property. Thus, when different but potentially coordinated nerve cells fire according to the same schedule time after time, they can coalesce into a cooperating group, which collectively determines how they respond. In such a fashion, the details of a map region are formed from its "little pieces."

After concluding that temporal correlations among inputs are important for establishing map details, Merzenich inferred that the activity of any single nerve cell is trivial. What is crucial is a nerve's role in a "network" where it becomes part of a vast repertoire of inputs garnered over time from experience. According to Edelman's model, selection is not individual neuron by neuron, but by groups of neurons. Merzenich says, "We've definitely confirmed this."

The description has Darwinian overtones—one of the basic tenets is that a competitive process is the driving force behind the behaviors that define a group of nerve cells. According to Edelman's more general model, a given region of the brain contains many more anatomical connections than it ultimately uses and thus competition determined by use pares down this "degeneracy."

The groups of neurons, which Merzenich describes within the somatosensory region of the cortex, act as "functional, floating entities" that span an area as much as 1 millimeter across. In the somatosensory region these entities typically are tens of microns across, and they weigh sensory inputs "not cell by cell but by several thousand" nerve cells at once, he says.

"I get a little better at a task each time I 'rehearse' it," Merzenich continues. This suggests that changes in the nervous system are somehow recorded, and the rules to describe how that occurs undoubtedly involve understanding how a change occurs across a network.

"People ask 'What does this neuron do?'," Merzenich says. "They imagine if they define it, that will be enough. But I think what it does is temporary and that, in fact, its role in the network depends on its history in that network. . . . If a neuron has a repertoire delivered to it from which it selects, what it does is respond according to its history." He believes there must be a way in which a vast array of signals is measured and, eventually, evaluated across such networks.

Merzenich speculates that these dynamic mechanisms, operating for the somatosensory system in monkey brains, could be the "basic ones underlying cognitive function." A general theory of cortical function, which includes the rules for how maps of sensations reorganize, must relate to cognitive function, he argues. For that to be true, he quickly adds, other factors would have to come into play besides mere temporal correlations of input within a group of nerve cells.

For example, an animal's state of awareness can make a big difference as to whether it learns a task rapidly or slowly. This must be true when it comes to modifying a somatosensory map, with the map's dynamic properties being far more evident when an animal is attentive than when it is bored.

Merzenich and his colleagues are in the very early stages of studying how minute physiological changes recorded in the brain may account for training and other behavioral changes in the monkeys. Many previous studies have employed what Merzenich regards as a "limited strategy," because they study brain function only at "static epochs"—for example, only after training is completed. "To my mind, what is most interesting has occurred during the period of training," he says. "The dynamic properties of neural networks should be the focus of our attention, but their study has been largely neglected."

Whether these dynamic properties of groups of nerve cells can account for learning and other behaviors in primates remains to be proved. However, those properties do seem to apply to both the somatosensory and auditory pathways of monkey brains.

Although experiments have not yet been done on the visual system, Merzenich expects that similar findings and rules will apply there, even though the organization of its neural components is believed to be "more rigidly anatomical." The visual cortex in the brain becomes organized into bands called ocular dominance columns that seem to be set within 3 months after birth in monkeys. This special feature "presumably limits dynamic alterability," forcing it to stay within the narrow boundaries of those bands, Merzenich notes. However, he asserts, "The differences in dynamism should be differences in degree, not in kind."

If truly general in the adult brain, these dynamic, self-organizing properties eventually could be tapped for more effective restoring of lost functions after brain injuries, assuming that appropriate methods can be developed to make use of these insights.—**JEFFREY L. FOX**

Additional Readings

1. M. M. Merzenich, R. J. Nelson, M. P. Stryker, M. S. Cynader, A. Schoppmann, J. M. Zook, *J. Comp. Neurol.* **224**, 591 (1984).
2. M. M. Merzenich, J. H. Kaas, J. T. Wall, M. Sur, R. J. Nelson, D. J. Felleman, *Neuroscience* **10**, 639 (1983).
3. G. M. Edelman and L. Finkel, in *Dynamic Aspects of Neocortical Function*, G. M. Edelman, W. M. Cowan, W. E. Gall, Eds. (Wiley, New York, 1984).