Phantom Limbs

People who have lost an arm or a leg often perceive the limb as though it is still there. They can also feel excruciating pain in specific parts of the phantom limb

by Ronald Melzack

In 1866 S. Weir Mitchell, the foremost American neurologist of his time, published his first account of phantom limbs, not in a scientific journal but in the *Atlantic Monthly,* as an anonymously written short story. In his tale, "The Case of George Dedlow," the protagonist loses an arm to amputation during the Civil War. Later, he awakens in the hospital after, unbeknownst to him, both his legs have also been amputated.

"[I was] suddenly aware of a sharp cramp in my left leg. I tried to get at it ...with my single arm, but, finding myself too weak, hailed an attendant. 'Just rub my left calf,... if you please.'"

"'Calf?...You ain't got none, pardner. It's took off.'"

Some historians have speculated that Mitchell chose to publish in the *Atlantic* as a way of testing the reaction of his peers to the concept of phantom limbs. He feared they would not believe amputated arms and legs could be felt after the limbs were gone.

In fact, the phenomenon of phantom limbs is common. So is the occurrence of terrible pain in these invisible appendages. Yet neither the cause of phantoms nor the associated suffering is well understood. My colleagues and I have recently proposed explanations that are leading to fresh research into treatments for the often intractable pain. The concepts also raise questions about basic assumptions of contemporary psychology and neuroscience.

RONALD MELZACK is E. P. Taylor Professor of Psychology at McGill University and research director of the Pain Clinic at Montreal General Hospital. His work on the neurophysiology of pain spans almost four decades. After obtaining his Ph.D. in psychology at McGill in 1954 and taking up fellowships in the U.S. and abroad, he joined the faculty of the Massachusetts Institute of Technology in 1959. There he and Patrick D. Wall began discussions that led to the publication in 1965 of their now famous "gate control" theory of pain. Melzack joined the McGill faculty in 1963. This is his fourth article for *Scientific American.*

The most extraordinary feature of phantoms is their reality to the amputee. Their vivid sensory qualities and precise location in space—especially at first—make the limbs seem so lifelike that a patient may try to step off a bed onto a phantom foot or lift a cup with a phantom hand. The phantom, in fact, may seem more substantial than an actual limb, particularly if it hurts.

In most cases, a phantom arm hangs straight down at the side when the person sits or stands, but it moves in perfect coordination with other limbs during walking; that is, it behaves like a normal limb. Similarly, a phantom leg bends as it should when its owner sits; it stretches out when the individual lies down; and it becomes upright during standing.

Sometimes, however, the amputee is sure the limb is stuck in some unusual position. One man felt that his phantom arm extended straight out from the shoulder, at a right angle to the body. He therefore turned sideways whenever he passed through doorways, to avoid hitting the wall. Another man, whose phantom arm was bent behind him, slept only on his abdomen or on his side because the phantom got in the way when he tried to rest on his back.

The eerie reality of phantoms is often reinforced by sensations that mimic feelings in the limb before amputation. For example, a person may feel a painful ulcer or bunion that had been on a foot or even a tight ring that had been on a finger. Such individuals are not merely recollecting sensations but are feeling them with the full intensity and detail of an ongoing experience. The reality of the phantom is also enhanced by wearing an artificial arm or leg; the phantom usually fills the prosthesis as a hand fits a glove.

The sense of reality is also strengthened by the wide range of sensations a phantom limb can have. Pressure, warmth, cold and many different kinds of pain are common. A phantom can feel wet (as when an artificial foot is seen stepping into a puddle). Or it can itch, which can be extremely distressing, although scratching the apparent site of discomfort can actually relieve the annoyance sometimes. The person may also feel as if the limb is being tickled or is sweaty or prickly.

Naturally, of all the sensations in phantom limbs, pain, which as many as 70 percent of amputees suffer, is the most frightening and disturbing. It is often described as burning, cramping or shooting and can vary from being occasional and mild to continuous and severe. It usually starts shortly after amputation but sometimes appears weeks, months or years later. A typical complaint is that a hand is clenched, fingers bent over the thumb and digging into the palm, so that the whole hand is tired and achy. In the leg the discomfort may be felt as a cramp in the calf. Many patients report that their toes feel as if they are being seared by a red-hot poker.

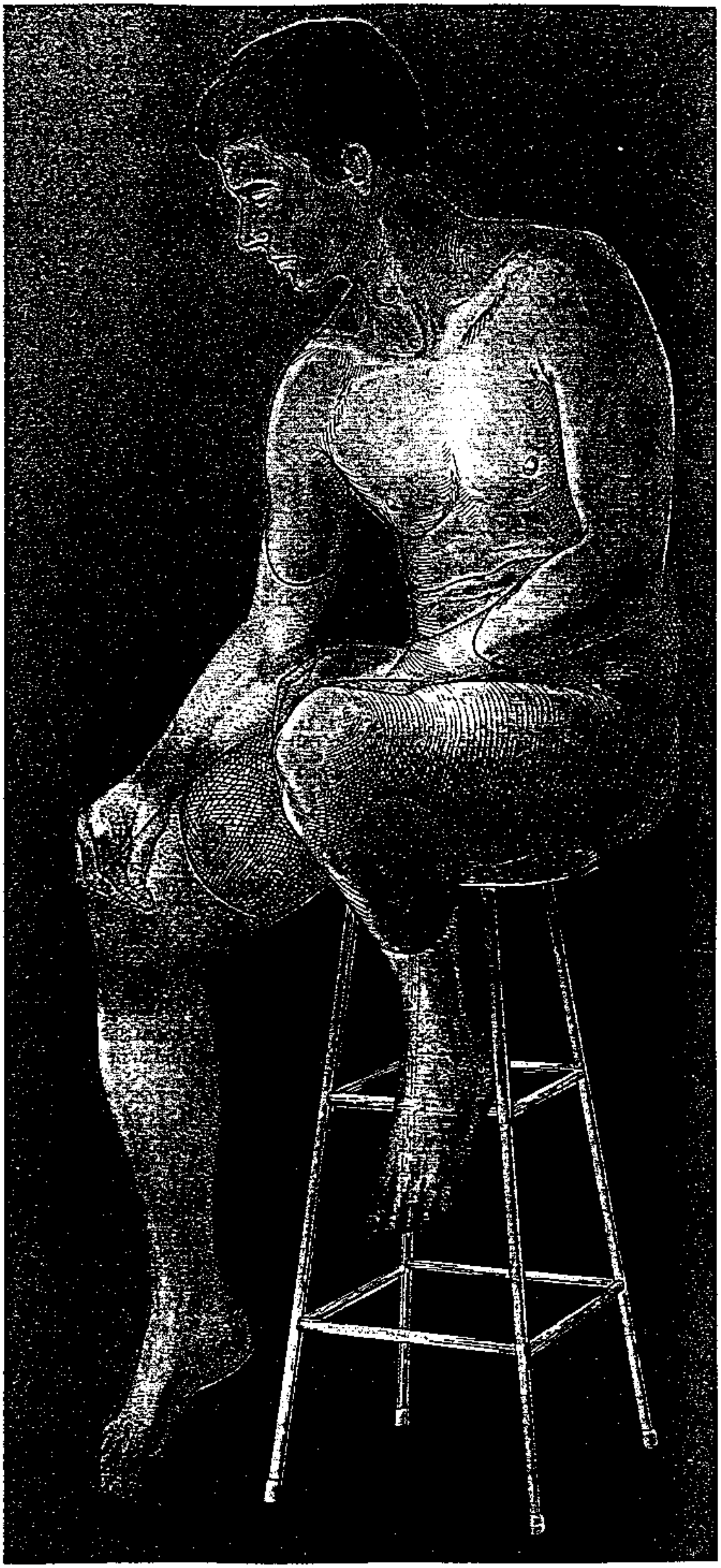
A final striking feature of phantoms, which reinforces the reality still further, is that they are experienced as a part of oneself. That is, patients perceive them as integral parts of the body. A phantom foot is described not only as real but as unquestionably belonging to the person. Even when the foot is felt to be dangling in the air several inches beneath the stump and unconnected to the leg, it is still experienced as part of one's body, and it moves appropriately with the other limbs and with the torso.

Amputation is not essential for the occurrence of a phantom. In some accidents, particularly when a rider is thrown off a motorcycle and hits the pavement, the shoulder is wrenched forward so that all the nerves from the arm are ripped from the spinal cord, a condition known as a brachial plexus avulsion. The resulting phantom occupies the now useless true arm and is usually coordinated with it. But if the victim's eyes are closed, the phantom will remain in its original position when the real arm is moved by someone else. Although the flesh-and-blood arm is incapable of responding to stimulation, the phantom version is usually extremely painful. Regrettably, surgical removal of the true arm has no effect on the phantom or the pain.

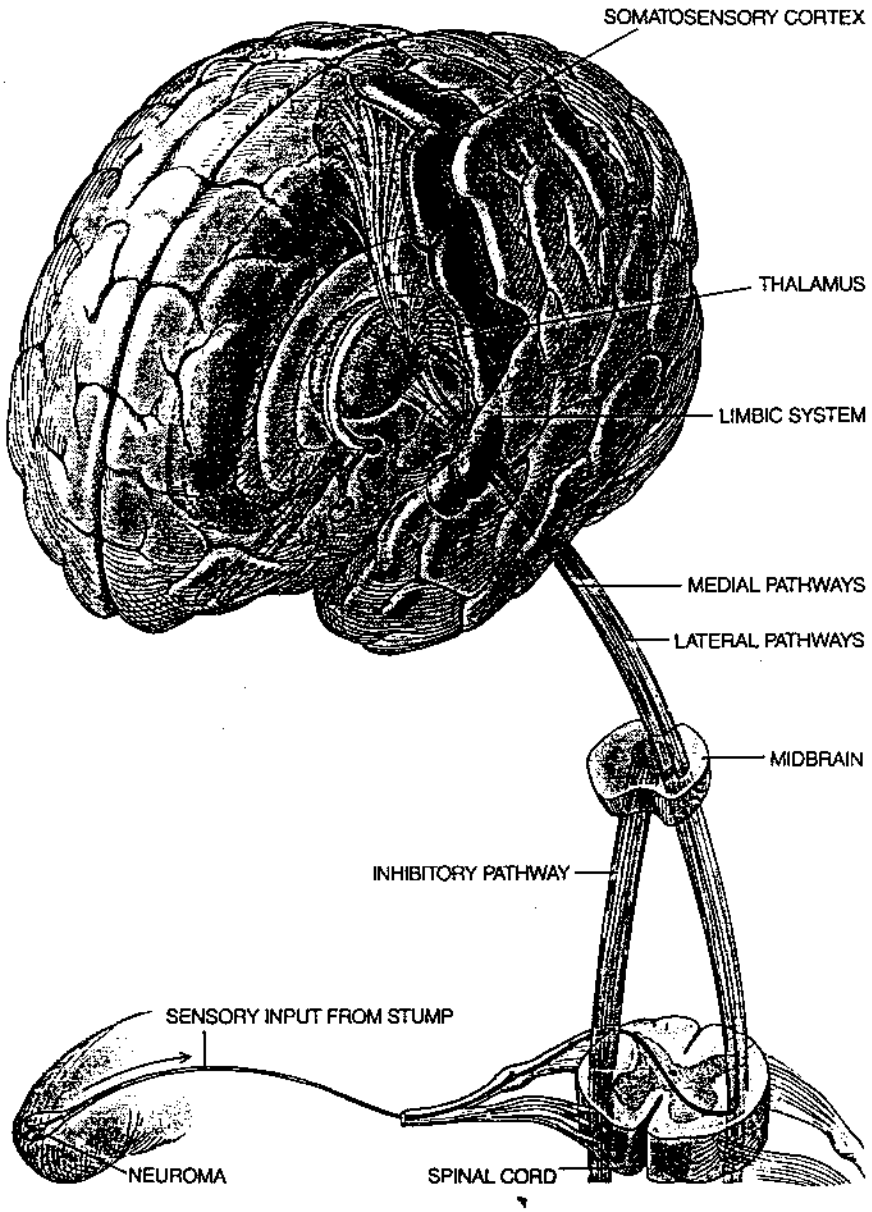
Similarly, paraplegics—persons who have had a complete break of the spinal cord and therefore have no feeling in, or control over, their body below the break—often have phantom legs and other body parts, including genitals. Immediately after an accident, the phantom may be dissociated from the real body. For instance, a person may feel as if the legs are raised over the chest or head even when he or she can see that they are stretched out on the road. Later, though, phantoms move in coordination with the body, at least when the person's eyes are open. Some paraplegics complain that their legs make continuous cycling movements, producing painful fatigue, even though a patient's actual legs are lying immobile on the bed. Phantoms are also reported by patients whose spinal cords are anesthetized, such as by a spinal block during labor.

The oldest explanation for phantom limbs and their associated pain is that the remaining nerves in the stump, which grow at the cut end into nodules called neuromas, continue to generate impulses. The impulses flow up through the spinal cord and parts of the thalamus (which is a central way station in the brain) to the somatosensory areas of the cortex. These cortical areas are the presumed centers for sensation in classical concepts of the nervous system.

On the basis of this explanation, treatments for pain have attempted to halt the transmission of impulses at every level of the somatosensory projection system. The nerves from the stump have been cut, usually just above the neuroma or at the roots—small bundles of fibers that arise when the sensory nerves divide into smaller



TYPICAL EXAMPLES of phantom limbs reported by patients are combined in this human figure. Some parts of the phantom are felt especially vividly (*highlighted areas in transparent limbs*). The phantom limb is perceived as perfectly real to the patient, who describes it as being in various positions and often reports feeling pain in it.



PATHWAYS OF SIGNALS from the body to the brain are shown. After the loss of a limb, nerve cells in the denervated areas of the spinal cord and brain fire spontaneously at high levels and with abnormal bursting patterns.

branches, just before they enter the spinal cord. Pathways within the spinal cord have been cut as well, and the areas of the thalamus and cortex that ultimately receive sensory information from the limb have been removed.

Although these approaches may provide relief for months or even years, the pain usually returns. Moreover, none of these procedures abolishes the phantom limb itself. Hence, neuroma activity cannot by itself account for either the phenomenon of the phantom limb or for the suffering.

A related hypothesis moves the source of phantom limbs from neuromas to the spinal cord, suggesting that phantoms arise from excessive, spontaneous firing of spinal cord neurons that have lost their normal sensory input from the body. The output of the cells is transmitted to the cortex, just as if the spinal neurons had received external stimulation. This proposal grew in part out of research done in the 1960s showing that after sensory nerves in the body are cut, neurons in the spinal cord spontaneously generate a high level of electrical impulses, often in an abnormal, bursting pattern.

Other observations indicate that this explanation is insufficient. Paraplegics who have suffered a complete break of the spinal cord high in the upper body sometimes feel severe pain in the legs and groin. Yet the spinal neurons that carry messages from those areas to the brain originate well below the level of the break, which means that any nerve impulses arising in those neurons would not traverse the break.

Some recent work has led to the proposal that phantom limbs can arise still higher in the central nervous system—in the brain itself. One hypothesis holds that phantoms are caused by changes in the flow of signals through the somatosensory circuit in the brain.

For example, Frederick A. Lenz, then at the University of Toronto, observed abnormally high levels of activity and a bursting pattern in cells of the thalamus in a paraplegic patient who had a full break of the spinal cord just below the neck but nonetheless suffered pain in the lower half of his body. The overactive cells, it turned out, also responded to touches of the head and neck, even though the cells were in the area of the thalamus that normally responds only to stimulation of the body below the level of the cut. This finding suggested that neural inhibition was lifted on the flow of signals across existing but previously unused synapses in sensory neurons projecting to the thalamus from the head and neck.

Such changes in the somatosensory thalamus or cortex could help explain why certain feelings arise in limbs that no longer exist or can no longer transmit signals to the brain. Nevertheless, alterations in this system cannot by themselves account for phantoms and their pain. If this explanation were sufficient, removal of the affected parts of the somatosensory cortex or thalamus would solve both problems.

Clearly, the source of phantom limbs is more complex than any of these theories would suggest. No other hypotheses have been proposed, however. As an outgrowth of my interest in the brain mechanisms that give rise to pain, I have pondered the causes of phantoms and phantom-limb pain and studied patients with these problems for many years.

My work and that of others have led me to conclude that, to a great extent, phantom limbs originate in the brain, as the work of Lenz would suggest. But much more of the cerebrum than the somatosensory system is involved.

Any explanation must account for the rich variety of sensations a person can feel, the intense reality of the phantom and the conviction that even free-floating phantoms belong to the self. I have proposed such a model. It has been well received, but it must, of course, be tested more fully before its value can be assessed completely. Meanwhile, though, it has already generated new ideas for research into stopping the pain that arises from phantom limbs.

In essence, I postulate that the brain contains a neuromatrix, or network of neurons, that, in addition to responding to sensory stimulation, continuously generates a characteristic pattern of impulses indicating that the body is intact and unequivocally one's own. I call this pattern a neurosignature. If such a matrix operated in the absence of sensory inputs from the periphery of the body, it would create the impression of having a limb even when that limb has been removed.

To produce all the qualities I have described for phantoms, the matrix would have to be quite extensive, including at least three major neural circuits in the brain. One of them, of course, is the classical sensory pathway passing through the thalamus to the somatosensory cortex.

A second system must consist of the pathways leading through the reticular formation of the brain stem to the limbic system, which is critical for emotion and motivation. I include this circuit in part because I and others have noted that paraplegics who suffer a complete spinal break high in the upper body continue to experience themselves as still being in their old body, and they describe the feelings in the denervated areas with the same kinds of affective terms as they did before they were injured, such as "painful," "pleasurable" or "exhausting."

A final system consists of cortical regions important to recognition of the self and to the evaluation of sensory signals. A major part of this system is the parietal lobe, which in studies of brain-damaged patients has been shown to be essential to the sense of self.

Indeed, patients who have suffered a lesion of the parietal lobe in one hemisphere have been known to push one of their own legs out of a hospital bed because they were convinced it belonged to a stranger. Such behavior shows that the damaged area normally imparts a signal that says, "This is my body; it is a part of my self."

I believe that when sensory signals from the periphery or elsewhere reach the brain, they pass through each of these systems in parallel. As the signals are analyzed, information about them is shared among the three systems and converted into an integrated output, which is sent to other parts of the brain. Somewhere in the brain the output is transformed into a conscious perception, although no one knows exactly where the transformation that leads to awareness takes place.

As dynamic as this description may seem, the processing is probably still more dynamic than that. I further propose that as the matrix analyzes sensory information, it imprints its characteristic neurosignature on the output. Thus, the output carries information about sensory input as well as the assurance that the sensation is occurring in one's own body. The neurosignature may be likened to the basic theme of an orchestral piece. The collective sound changes when different instru-

Phantom Seeing and Hearing

Phantom seeing and hearing, like phantom limbs, are also generated by the brain in the absence of sensory input. People whose vision has been impaired by cataracts or by the loss of a portion of the visual processing system in the brain sometimes report highly detailed visual experiences. This syndrome was first described in 1769, when the philosopher Charles Bonnet wrote an article on the remarkable visual experiences of his grandfather, Charles Lullin, who had lost most of his vision because of cataracts but was otherwise in good physical and psychological health. Since then, many mentally sound individuals have reported similarly vivid phantom visual experiences.

Phantom seeing often coexists with a limited amount of normal vision. The person experiencing the phantom has no difficulty in differentiating between the two kinds of vision. Phantom visual episodes appear suddenly and unexpectedly when the eyes are open. People usually describe the visual phantoms as seeming real despite the obvious impossibility of their existence. Common phantom images include people and large buildings. Rarer perceptions include miniature people and small animals. Phantom sights are not mere memories of earlier experiences; they often contain events, places or people that have never before been encountered.

First appearances of phantom images can be quite startling. A woman in one of our studies who had lost much of her vision because of retinal degeneration reported being shocked when she looked out a window and saw a tall building in what she knew to be a wooded field. Even though she realized that the building was a phantom, it seemed so real that she could count its steps and describe its other details. The building soon disappeared, only to return several hours later. The phantom vision continues to come and go unexpectedly, she told my student Geoffrey Schultz.

Phantom seeing occurs most among the elderly, presumably because vision tends to deteriorate with age. Some 15 percent of the people who lose all or part of their vision report phantom visual experiences. The proportion may be higher because some people avoid discussing phantom vision for fear of being labeled as psychologically disturbed.

Phantom sounds are also extremely common, although few people recognize them for what they are. People who lose their hearing commonly report noises in their heads. These noises, called tinnitus, are said to sound like whistling, clanging, screeching or the roaring of a train. They can be so loud and unpleasant that the victim needs help to cope with the distress they cause.

Some people with tinnitus report hearing "formed sounds," such as music or voices. A woman who had been a musician before losing her hearing says she "hears" piano concertos and sonatas. The impression is so real that at first she thought the sounds were coming from a neighbor's radio. The woman reports that she cannot turn off the music and that it often gets louder at night when she wants to go to sleep. Another woman, who had lost much of her sight and hearing, experienced both phantom sight and sound. In one instance, she delightedly described seeing a circus and hearing the music that accompanied the acts.

Phantom sights and sounds, like phantom limbs, occur when the brain loses its normal input from a sensory system. In the absence of input, cells in the central nervous system become more active. The brain's intrinsic mechanisms transform that neuronal activity into meaningful experiences.

ments play their parts (the input), but the product is continually shaped by the underlying theme (the neurosignature), which provides the continuity for the work, even as the details of its rendition change.

The specific neurosignature of an individual would be determined by the pattern of connectivity among neurons in the matrix—that is, by such factors as which neurons are connected to one another and by the number, types and strengths of the synapses. Readers familiar with neuroscience will note that my conception of the neuromatrix has similarities to the notion of the cell assembly proposed long ago by Donald O. Hebb of McGill University. Hebb argued that when sensory input activates two brain cells simultaneously, synapses between the cells form stronger connections. Eventually the process gives rise to whole assemblies of linked neurons, so that a signal going into one part of an assembly spreads through the rest, even if the assembly extends across broad areas of the brain.

I depart from Hebb, however, in that I visualize the neuromatrix as an assembly whose connections are primarily determined not by experience but by the genes. The matrix, though, could later be sculpted by experience, which would add or delete, strengthen or weaken, existing synapses. For instance, experience would enable the matrix to store the memory of a pain from a gangrenous ulcer and might thus account for the frequent reappearance of the same pain in phantom limbs.

I think the matrix is largely prewired, for the simple reason that my colleagues and I have encountered many people who were born without an arm or a leg and yet experience a vivid phantom. For example, an intelligent and serious eight-year-old boy, who was born with paralyzed legs and a right arm that ends at the elbow, tells us that when he fits his elbow into a small cup so as to manipulate a lever that allows him to move his wheelchair, phantom fingers, "like everyone else's fingers," emerge from his elbow and grasp the edges of the cup. Phantoms such as these may persist into adulthood: a 32-year-old engineer who was born without a leg below the knee reports that his phantom leg and foot remain vivid but vanish for several hours once or twice a week. He is always astonished and delighted when they return.

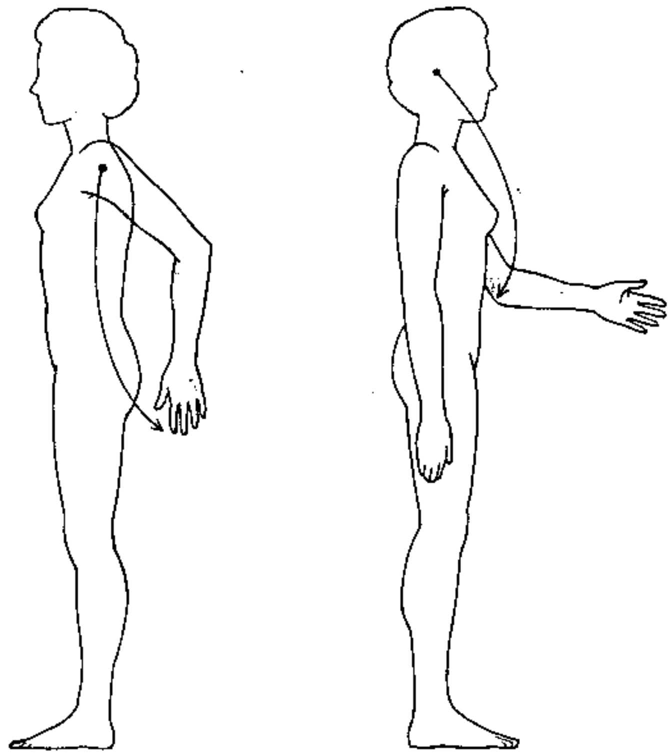
Parenthetically, I should note that the long-held belief that phantoms are experienced only when an amputation has occurred after the age of six or seven is not true. My postdoctoral student Renée Lacroix and I have confirmed earlier reports that children who lose a limb when they are as young as one or two years old can have phantom limbs. We have also encountered children who have painful phantoms of legs lost before age two.

Under normal circumstances, then, the myriad qualities of sensation people experience emerge from variations in sensory input. This input is both analyzed and shaped into complex experiences of sensation and self by the largely prewired neuromatrix. Yet even in the absence of external stimuli, much the same range of experiences can be generated by other signals passing through the neuromatrix—such as those produced by the spontaneous firing of neurons in the matrix itself or the spinal cord or produced by neuromas. Regardless of the source of the input to the matrix, the result would be the same: rapid spread of the signals throughout the matrix and perception of a limb located within a unitary self, even when the actual limb is gone.

The fading of phantom limbs and their pain, which sometimes occurs over time, would be explained if cerebral neurons that once responded to lost or paralyzed limbs develop increasingly strong connections with still sensate parts of the body and then begin to serve those regions. In the process the neurosignature pattern would change, resulting in changes in the phantom and the pain. But phantoms do not usually disappear forever. In fact, they may return decades after they seem to have gone, which indicates that the neuromatrix, even when modified, retains many of its features permanently.

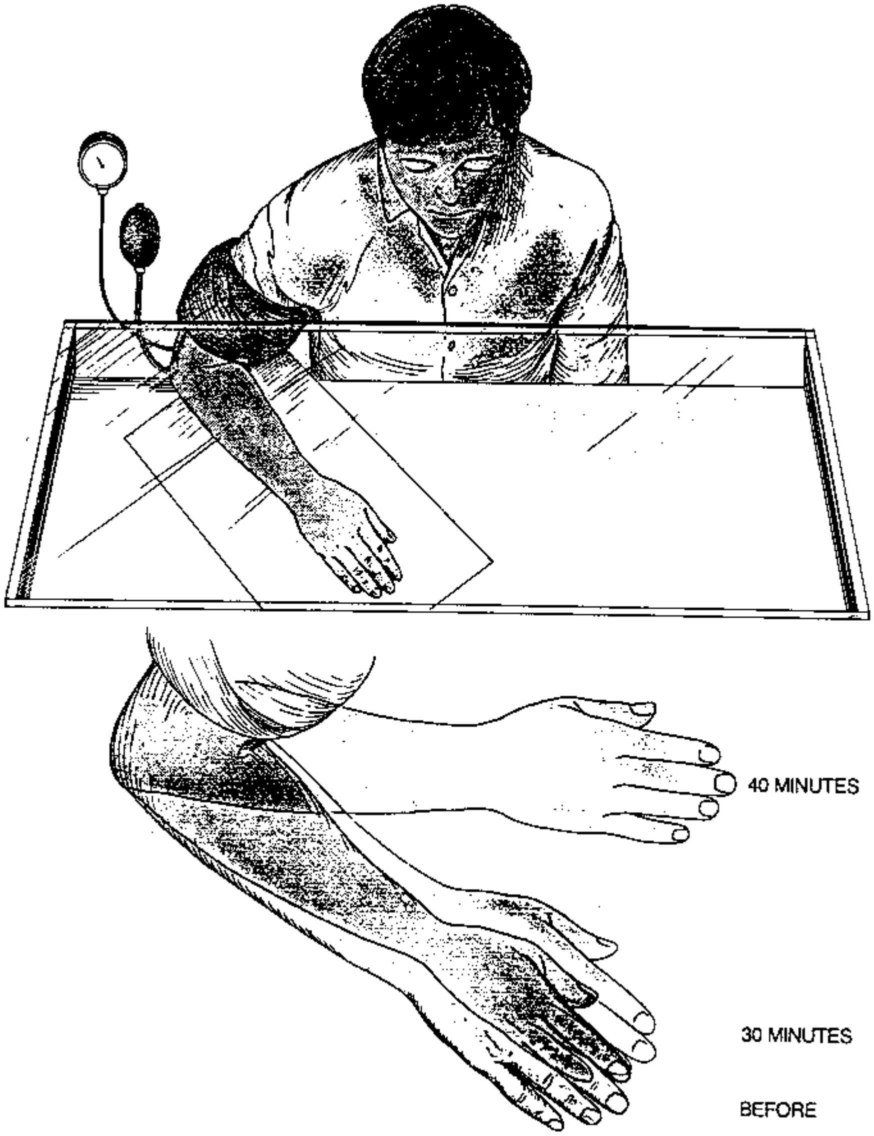
My students Anthony L. Vaccarino, John E. McKenna and Terence J. Coderre and I have already gathered some direct evidence supporting my suggestion that the brain—and by implication, the neuromatrix—can generate sensation on its own. Our studies relied on what is called the formalin pain test.

We injected a dilute solution of formalin (formaldehyde dissolved in water) under the skin of a rat's paw, which produces pain that rapidly rises and falls in intensity during the first five minutes after the injection. (The degree and duration of discomfort are assessed by such behaviors as licking the paw.) This "early" response is followed by "late" pain, which begins about 15 minutes after the injection and persists for about an hour.



REFERRED SENSATIONS in a painful phantom arm were reported by a woman receiving electrical stimuli at two different places (*dots*). Stimulation at the stump gave the sensation of electric shocks that jumped from finger to finger. Stimulation on the right ear made the phantom elbow feel warm and caused a pulsing sensation that traveled down the phantom wrist and thumb. The observations were made by Joel Katz, now at the University of Toronto, and the author.

By means of this test, we found that an anesthetic block of the paw completely obliterates the late pain, but only if the anesthetic is delivered in time to prevent the early response. Once the early pain occurs, the drug only partly reduces the later response. This observation of pain continuing even after the nerves carrying pain signals are blocked implies that long-lasting pain (such as that in phantoms) is determined not only by sensory stimulation during the discomfort but also by brain processes that persist without continual priming.



REAL ARM made insensate by an inflated pressure cuff resembles a phantom arm. The subject could not see the arm, because the table was covered by a black cloth. The positions of the hand felt before the cuff was inflated and at intervals thereafter, as the hand seemed to be closer to the body, are shown. This study was carried out with Yigal Gross, now at Bar-Ilan University in Israel.

But what exactly causes the pain in phantom limbs? The most common complaint is a burning sensation. This feeling could stem from the loss of sensory signaling from the limb to the neuromatrix. Without its usual sensory stimulation, the neuromatrix would probably produce high levels of activity in a bursting pattern, such as Lenz observed in the thalamus. This kind of signal may very well be transformed into an awareness of burning.

Other pain may result from the effort of the neuromatrix to make the limbs move as they normally would. When the limbs do not respond in amputees and paraplegics, the neuromatrix (which would be prewired to "assume" the limbs can indeed move) may issue more frequent and stronger messages urging the muscles to move the limb. These outputs may be perceived as cramping. Similar output messages might also be felt as shooting pain.

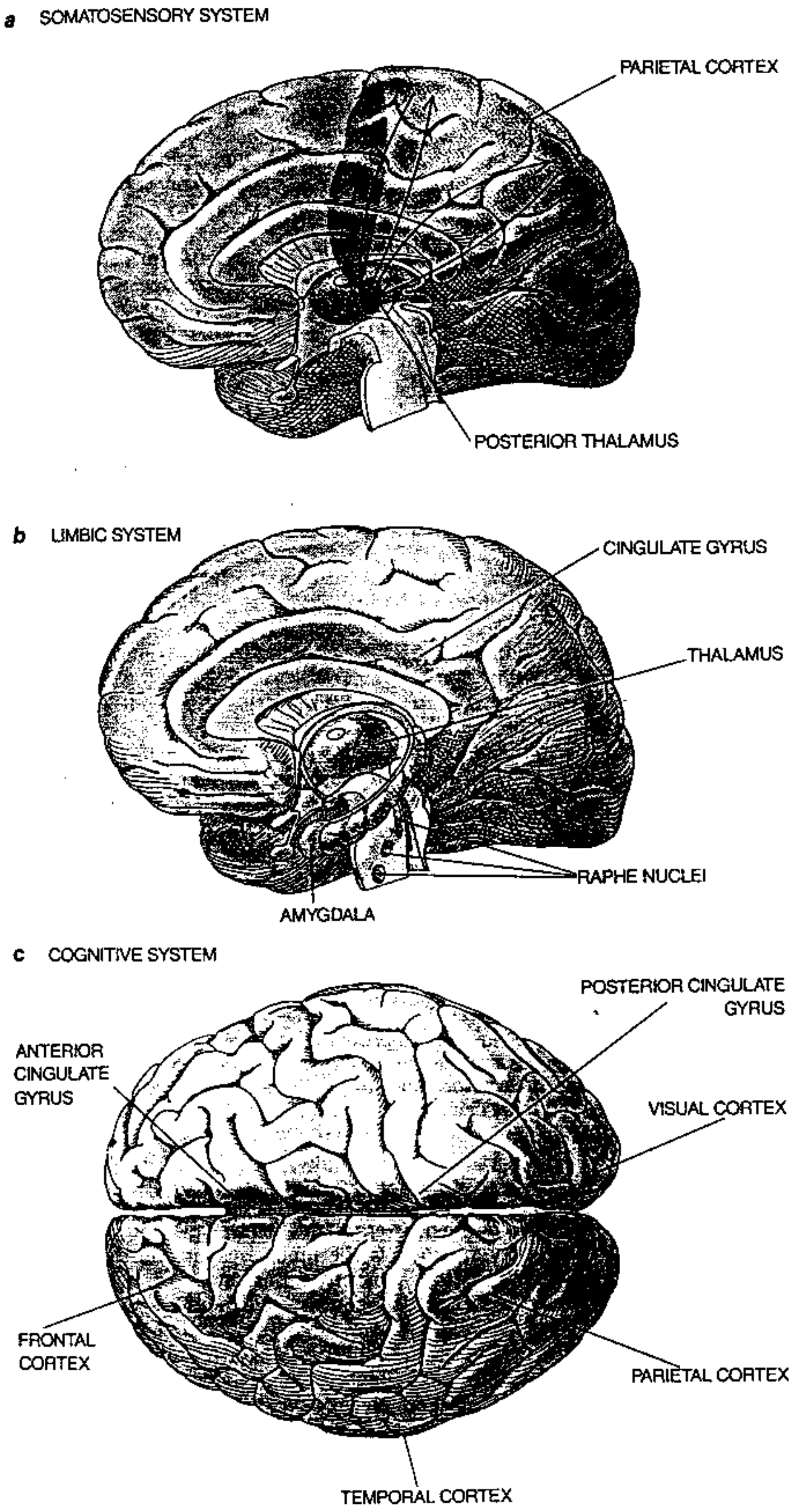
Research to test some of these ideas and explore new ways of eliminating pain is still in its infancy, but some intriguing results are beginning to emerge. The need for such treatments is urgent, both because the suffering can be severe and persistent and because, sadly, few existing methods are permanently effective.

At the moment, a number of different therapies are used. Stimulation of the stump with electric currents, a vibrator or acupuncture helps some amputees. Relaxation and hypnosis aid others. Some individuals obtain considerable relief from drugs that are usually given to counteract epilepsy or depression, and other patients find their pain is eased by a combination of an antidepressant and a narcotic (such as methadone). But about half of those with persistent, long-term phantom pain fail to respond to any approach.

On a more promising note, an experimental treatment called the DREZ (dorsal root entry zone) procedure selectively abolishes phantom-limb pain, but not the phantoms themselves, in about 60 percent of the patients treated. In this method, developed by Blaine S. Nashold of Duke University, neurosurgeons destroy the spinal cells that receive input directly from the sensory nerves of the stump, specifically eliminating the cells at the site where the sensory roots enter the spinal cord. (Past efforts at dampening the somatosensory projection system generally cut the sensory roots or the transmission pathways in the spinal cord.) The DREZ procedure is so new that no one yet knows how long the relief persists.

Because my model of brain functioning posits that the neuromatrix as a whole may contribute to pain, the model also suggests that altering the activity of pathways outside the somatosensory system might be important, either alone or in combination with other treatments. One place to begin work is the limbic system. Until now, limbic structures have been relegated to a secondary role in efforts to treat pain, because injurious stimuli do not activate them directly. Nevertheless, if the limbic system contributes to output by the neuromatrix, as I have proposed, it might well contribute to the pain felt in phantom limbs.

Vaccarino, McKenna, Coderre and I have begun to test the value of manipulating the limbic system as a way of easing pain. We have shown that localized injection of lidocaine (a relative of cocaine that prevents neurons from transmitting signals) into diverse areas of the limbic system produces striking decreases in several types of experimen-



SOURCE OF PHANTOM LIMBS is thought by the author to involve activity in three of the brain's neural circuits. One of them (*a*) is the somatosensory receiving areas and the adjacent parietal cortex, which process information related to the body. The second area (*b*) is the limbic system, which is concerned with emotion and motivation. The third (*c*) encompasses the widespread cortical networks involved in cognitive activities, among them the memory of past experience and the evaluation of sensory inputs in relation to the self.

tally produced pain in rats, including a model of phantom-limb pain. A similar approach could be feasible in humans but needs more study.

The phenomenon of phantom limbs is more than a challenge to medical management. It raises doubts about some fundamental assumptions in psychology. One such assumption is that sensations are produced only by stimuli and that perceptions in the absence of stimuli are psychologically abnormal. Yet phantom limbs, as well as phantom seeing and hearing, indicate this notion is wrong. The brain does more than detect and analyze inputs; it generates perceptual experience even when no external inputs occur. We do not need a body to feel a body.

Another entrenched assumption is that perception of one's body results from sensory inputs that leave a memory in the brain; the total of these signals becomes the body image. But the existence of phantoms in people born without a limb or who have lost a limb at an early age suggests that the neural networks for perceiving the body and its parts are built into the brain. The absence of inputs does not stop the networks from generating messages about missing body parts; they continue to produce such messages throughout life.

In short, phantom limbs are a mystery only if we assume the body sends sensory messages to a passively receiving brain. Phantoms become comprehensible once we recognize that the brain generates the experience of the body. Sensory inputs merely modulate that experience; they do not directly cause it.

FURTHER READING

BODY IMAGE: DISSOCIATION OF REAL AND PERCEIVED LIMBS BY PRESSURE-CUFF ISCHEMIA. Y. Gross and R. Melzack in *Experimental Neurology*, Vol. 61, No. 3, pages 680–688; September 15, 1978.

PHANTOM LIMBS, THE SELF AND THE BRAIN: THE D. O. HEBB MEMORIAL LECTURE. R. Melzack in *Canadian Psychology*, Vol. 30, No. 1, pages 1–16; January 1989.

CENTRAL NERVOUS SYSTEM PLASTICITY IN THE TONIC PAIN RESPONSE TO SUBCUTANEOUS FORMALIN INJECTION. T. J. Coderre, A. L. Vaccarino and R. Melzack in *Brain Research*, Vol. 535, No. 1, pages 155–158; December 3, 1990.

PAIN "MEMORIES" IN PHANTOM LIMBS: REVIEW AND CLINICAL OBSERVATIONS. J. Katz and R. Melzack in *Pain*, Vol. 43, No. 3, pages 319–336; December 1990.

THE ROLE OF THE CINGULUM BUNDLE IN SELF-MUTILATION FOLLOWING PERIPHERAL NEURECTOMY IN THE RAT. A. L. Vaccarino and R. Melzack in *Experimental Neurology*, Vol. 111, No. 1, pages 131–134; January 1991.