Phantom Limbs

*The Author*

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.*

Stimulation elsewhere in the body can sometimes be felt in a phantom limb.
People who have lost an arm or a leg often perceive the limb as though it were still there.

Treating the pain of these ghostly appendages remains difficult

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.

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 sometimes actually relieve the annoyance. 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 acci-

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 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.

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Phantom Limbs

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 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 abolish the phantom limb itself. Hence, neuroma activity cannot by itself account either for 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...
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 explained to 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 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.

—R.M.
sical 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 instruments 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.

Genetically Prewired Matrix

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 reports that 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 that were 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 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 that is 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. Codere 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.

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.

Phantom-Limb Pain

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 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.
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.

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 function-