CHAPTER 3

Chasing the Phantom

You never identify yourself with the shadow cast by your body, or with its reflection, or with the body you see in a dream or in your imagination. Therefore you should not identify yourself with this living body, either.

—*SHANKARA (A.D. 788–820),* Viveka Chudamani *(Vedic scriptures)*

When a reporter asked the famous biologist J.B.S. Haldane what his biological studies had taught him about God, Haldane replied, "The creator, if he exists, must have an inordinate fondness for beetles," since there are more species of beetles than any other group of living creatures. By the same token, a neurologist might conclude that God is a cartographer. He must have an inordinate fondness for maps, for everywhere you look in the brain maps abound. For example, there are over thirty different maps concerned with vision alone. Likewise for tactile or somatic sensations—touch, joint and muscle sense—there are several maps, including, as we saw in the previous chapter, the famous Penfield homunculus, a map draped across a vertical strip of cortex on the sides of the brain. These maps are largely stable throughout life, thus helping ensure that perception is usually accurate and reliable. But, as we have seen, they are also being constantly updated and refined in response to vagaries of sensory input. Recall that when Tom's arm was amputated, the large patch of cortex corresponding to his missing hand was "taken over" by sensory input from his face. If I touch Tom's face, the sensory message now goes to two areas—the original face area (as it should) but also the original "hand area." Such brain map alterations may help explain the appearance of Tom's phantom limb soon after amputation. Every time he smiles or experiences some spontaneous activity of facial nerves, the activity stimulates his "hand area," thereby fooling him into thinking that his hand is still there.

But this cannot be the whole story. First, it doesn't explain why so many people with phantoms claim that they can move their "imaginary" limbs voluntarily. What is the source of this illusion of movement? Second, it doesn't explain the fact that these patients sometimes experience intense agony in the missing limb, the phenomenon called phantom pain. Third, what about a person who is born without an arm? Does remapping also occur in his brain, or does the hand area of the cortex simply never develop because he never had an arm? Would he experience a phantom? Can someone be *born* with phantom limbs?

The idea seems preposterous, but if there's one thing I've learned over the years it's that neurology is full of surprises. A few months after our first report on phantoms had been published, I met Mirabelle Kumar, a twenty-five-year-old Indian graduate student, referred to me by Dr. Sathyajit Sen, who knew about my interest in phantoms. Mirabelle was born without arms. All she had were two short stumps dangling from her shoulders. X rays revealed that these stumps contained the head of the humerus or upper arm bone, but that there were no signs of a radius or ulna. Even the tiny bones of her hands were missing, although she did have a hint of rudimentary fingernails in the stump.

Mirabelle walked into my office on a hot summer day, her face flushed from walking up three flights of stairs. An attractive, cheerful young lady, she was also extremely direct with a "don't pity me" attitude writ large on her face.

As soon as Mirabelle was seated, I began asking simple questions: where she was from, where she went to school, what she was interested in and so forth. She quickly lost patience and said, "Look, what do you really want to know? You want to know if I have phantom limbs, right? Let's cut the crap."

I said, "Well, yes, as a matter of fact, we do experiments on phantom limbs. We're interested in . . ."

She interrupted. "Yes. Absolutely. I've never had arms. All I've ever had are these." Deftly, using her chin to help her in a practiced move, she took off her prosthetic arms, clattered them onto my desk and held up her stumps. "And yet I've always experienced the most vivid phantom limbs, from as far back in my childhood as I can remember."

I was skeptical. Could it be that Mirabelle was just engaging in wishful thinking? Maybe she had a deep-seated desire to conform, to be normal. I was beginning to sound like Freud. How could I be sure she was not making it up?

I asked her, "How do you know that you have phantom limbs?"

"Well, because as I'm talking to you, they are gesticulating. They point to objects when I point to things, just like your arms and hands."

I leaned forward, captivated.

"Another interesting thing about them, doctor, is that they're not as long as they should be. They're about six to eight inches too short."

"How do you know that?"

"Because when I put on my artificial arms, my phantoms are much shorter than they should be," said Mirabelle, looking me squarely in the eye. "My phantom fingers should fit into the artificial fingers, like a glove, but my arm is about six inches too short. I find this incredibly frustrating because it doesn't feel natural. I usually end up asking the prosthetist to reduce the length of my artificial arms, but he says that would look short and funny. So we compromise. He gives me limbs that are shorter than most but not so absurdly short that they look strange." She pointed to one of her prosthetic arms lying on the desk, so I could see. "They're a little bit shorter than normal arms, but most people don't notice it."

To me this was proof that Mirabelle's phantoms were not wishful thinking. If she wanted to be like other people, why would she want shorter-than-normal arms? There must be something going on inside her brain that was giving rise to the vivid phantom experience.

Mirabelle had another point. "When I walk, doctor, my phantom arms don't swing like normal arms, like your arms. They stay frozen on the side, like this." She stood up, letting her stumps drop straight down on both sides. "But when I talk," she said, "my phantoms gesticulate. In fact, they're moving now as I speak."

This is not as mysterious as it sounds. The brain region responsible for smooth, coordinated swinging of the arms when we walk is quite different from the one that controls gesturing. Perhaps the neural circuitry for arm swinging cannot survive very long without continuous nurturing feedback from the limbs. It simply drops out or fails to develop when the arms are missing. But the neural circuitry for gesticulation—activated during spoken language—might be specified by genes during development. (The relevant circuitry probably antedates spoken language.) Remarkably, the neural circuitry that generates these commands in Mirabelle's brain seems to have survived intact, despite the fact that she has received no visual or kinesthetic feedback from those "arms" at any point in her life. Her body keeps telling her, "There are no arms, there are no arms," yet she continues to experience gesticulation.

This suggests that the neural circuitry for Mirabelle's body image must have been laid down at least partly by genes and is not strictly dependent on motor and tactile experience. Some early medical reports claim that patients with limbs missing from birth do not experience phantoms. What I saw in Mirabelle, however, implies that each of us has an internally hard-wired image of the body and limbs at birth—an image that can survive indefinitely, even in the face of contradictory information from the senses.[1]

In addition to these spontaneous gesticulations, Mirabelle can also generate voluntary movements in her phantom arms, and this is also true of patients who lose arms in adulthood. Like Mirabelle, most of these patients can "reach out" and "grab" objects, point, wave good-bye, shake hands, or perform elaborate skilled maneuvers with the phantom. They know it sounds crazy since they realize that the arm is gone, but to them these sensory experiences are very real.

I didn't realize how compelling these felt movements could be until I met John McGrath, an arm amputee who telephoned me after he had seen a television news story on phantom limbs. An accomplished amateur athlete, John had lost his left arm just below the elbow three years earlier. "When I play tennis," he said, "my phantom will do what it's supposed to do. It'll want to throw the ball up when I serve or it will try to give me balance in a hard shot. It's always trying to grab the phone. It even waves for the check in restaurants," he said with a laugh.

John had what is known as a telescoped phantom hand. It felt as if it were attached directly to his stump with no arm in between. However, if an object such as a teacup were placed a foot or two away from the stump, he could try to reach for it. When he did this, his phantom no longer remained attached to the stump but felt as if it were zooming out to grab the cup.

On a whim I started thinking, What if I ask John to reach out and grab this cup but pull it away from him before he "touches" it with his phantom? Will the phantom stretch out, like a cartoon character's rubbery arm, or will it stop at a natural arm's length? How far can I move the cup away before John will say he can't reach it? Could he grab the moon? Or will the physical limitations that apply to a real arm also apply to the phantom?

I placed a coffee cup in front of John and asked him to grab it. Just as he said he was reaching out, I yanked away the cup.

"Ow!" he yelled. "Don't do that!"

"What's the matter? "

"Don't do that," he repeated. "I had just got my fingers around the cup handle when you pulled it. That really hurts!"

Hold on a minute. I wrench a real cup from phantom fingers and the person yells, ouch! The fingers were illusory, of course, but the pain was real—indeed, so intense that I dared not repeat the experiment.

My experience with John started me wondering about the role of vision in sustaining the phantom limb experience. Why would merely "seeing" the cup be pulled away result in pain? But before we answer this question, we need to consider why anyone would experience movements in a phantom limb. If you close your eyes and move your arm, you can of course feel its position and movement quite vividly partly because of joint and muscle receptors. But neither John nor Mirabelle has such receptors. Indeed, they have no arm. So where do these sensations originate?

Ironically, I got the first clue to this mystery when I realized that many phantom limb patients—perhaps one third of them—are ***not*** able to move their phantoms. When asked, they say, "My arm is cast in cement, doctor" or "It's immobilized in a block of ice." "I try to move my phantom, but I can't," said Irene, one of our patients. "It won't obey my mind. It won't obey my command." Using her intact arm, Irene mimicked the position of her phantom arm, showing me how it was frozen in an odd, twisted position. It had been that way for a whole year. She always worried that she would "bump" it when entering doorways, and that it would hurt even more.

How can a phantom—a nonexistent limb—be paralyzed? It sounds like an oxymoron.

I looked up the case sheets and found that many of these patients had had preexisting pathology in the nerves entering the arm from the spinal cord. Their arms really had been paralyzed, held in a sling or cast for a few months and later been amputated simply because they were constantly getting in the way. Some patients were advised to get rid of it, perhaps in a misguided attempt to eliminate the pain in the arm or to correct postural abnormalities caused by the paralyzed arm or leg. Not surprisingly, after the operations these patients often experience a vivid phantom limb, but to their dismay the phantom remains locked in the same position as before the amputation, as though a memory of the paralysis is carried over into the phantom limb.

So here we have a paradox. Mirabelle never had arms in her entire life, yet she can move her phantoms. Irene had just lost her arm a year earlier and yet she cannot generate a flicker of movement. What's going on here?

To answer this question we need to take a closer look at the anatomy and physiology of the motor and sensory systems in the human brain. Consider what happens when you or I close our eyes and gesticulate. We have a vivid sense of our body and of the position of our limbs and their movements. Two eminent English neurologists, Lord Russell Brain and Henry Head (yes, these are their real names), coined the phrase "body image" for this vibrant, internally constructed ensemble of experiences—the internal image and memory of one's body in space and time. To create and maintain this body image at any given instant, your parietal lobes combine information from many sources: the muscles, joints, eyes and motor command centers.

When you decide to move your hand, the chain of events leading to its movements originates in the frontal lobes—especially in the vertical strip of cortical tissue called the motor cortex. This strip lies just in front of the furrow that separates the frontal lobe from the parietal lobe. Like the sensory homunculus that occupies the region just behind this furrow, the motor cortex contains an upside-down "map" of the whole body—except that it is concerned with sending signals to the muscles rather than receiving signals from the skin.

Experiments show that the primary motor cortex is concerned mainly with simple movements like wiggling your finger or smacking your lips. An area immediately in front of it, called the supplementary motor area, appears to be in charge of more complex skills such as waving good-bye and grabbing a banister. This supplementary motor area acts like a kind of master of ceremonies, passing specific instructions about the proper sequence of required movements to the motor cortex. Nerve impulses that will then direct these movements travel from the motor cortex down the spinal cord to the muscles on the opposite side of the body, allowing you to wave good-bye or put on lipstick.

Every time a "command" is sent from the supplementary motor area to the motor cortex, it goes to the muscles and they move.[2] At the same time, identical copies of the command signal are sent to two other major "processing" areas—the cerebellum and the parietal lobes—informing them of the intended action.

Once these command signals are sent to the muscles, a feedback loop is set in motion. Having received a command to move, the muscles execute the movement. In turn, signals from the muscle spindles and joints are sent back up to the brain, via the spinal cord, informing the cerebellum and parietal lobes that "yes, the command is being performed correctly." These two structures help you compare your intention with your actual performance, behaving like a thermostat in a servo-loop, and modifying the motor commands as needed (applying brakes if they are too fast and increasing the motor outflow if it's too slow). Thus intentions are transformed into smoothly coordinated movements.

Now let's return to our patients to see how all this relates to the phantom experience. When John decides to move his phantom arm, the front part of his brain still sends out a command message, since this particular part of John's brain doesn't "know" that his arm is missing—even though John "the person" is unquestionably aware of the fact. The commands continue to be monitored by the parietal lobe and are felt as movements. But they are phantom movements carried out by a phantom arm.

Thus the phantom limb experience seems to depend on signals from at least two sources. The first is remapping; recall that sensory input from the face and upper arm activates brain areas that correspond to the "hand." Second, each time the motor command center sends signals to the missing arm, information about the commands is also sent to the parietal lobe containing our body image. The convergence of information from these two sources results in a dynamic, vibrant image of the phantom arm at any given instant—an image that is continuously updated as the arm "moves."

In the case of an actual arm there is a third source of information, namely, the impulses from the joints, ligaments and muscle spindles of that arm. The phantom arm of course lacks these tissues and their signals, but oddly enough this fact does not seem to prevent the brain from being fooled into thinking that the limb is moving—at least for the first few months or years after amputation.

This takes us back to an earlier question. How can a phantom limb be paralyzed? Why does it remain "frozen" after amputation? One possibility is that when the actual limb is paralyzed, lying in a sling or brace, the brain sends its usual commands—move that arm, shake that leg.

The command is monitored by the parietal lobe, but this time it does not receive the proper visual feedback. The visual system says, "nope, this arm is not moving." The command is sent out again—arm, move. The visual feedback returns, informing the brain repeatedly that the arm isn't moving. Eventually the brain learns that the arm does not move and a kind of "learned paralysis" is stamped onto the brain's circuitry. Exactly where this occurs is not known, but it may lie partly in motor centers and partly in parietal regions concerned with body image. Whatever the physiological explanation turns out to be, when the arm is later amputated, the person is stuck with that revised body image: a paralyzed phantom.

If you can learn paralysis, is it possible that you can unlearn it? What if Irene were to send a "move now" message to her phantom arm, and every time she did so she got back a visual signal that it was moving; that, yes, it was obeying her command? But how can she get visual feedback when she doesn't have an arm? Can we trick her eyes into actually seeing a phantom?

I thought about virtual reality. Maybe we could create the visual illusion that the arm was restored and was obeying her commands. But that technology, costing over half a million dollars, would exhaust my entire research budget with one purchase. Fortunately, I thought of a way to do the experiment with an ordinary mirror purchased from a five-and-dime store.

To enable patients like Irene to perceive real movement in their nonexistent arms, we constructed a virtual reality box. The box is made by placing a vertical mirror inside a cardboard box with its lid removed. The front of the box has two holes in it, through which the patient inserts her "good hand" (say, the right one) and her phantom hand (the left one). Since the mirror is in the middle of the box, the right hand is now on the right side of the mirror and the phantom is on the left side. The patient is then asked to view the reflection of her normal hand in the mirror and to move it around slightly until the reflection appears to be superimposed on the felt position of her phantom hand. She has thus created the illusion of observing two hands, when in fact she is only seeing the mirror reflection of her intact hand. If she now sends motor commands to both arms to make mirror symmetric movements, as if she were conducting an orchestra or clapping, she of course "sees" her phantom moving as well. Her brain receives confirming visual feedback that the phantom hand is moving correctly in response to her command. Will this help restore voluntary control over her paralyzed phantom?

The first person to explore this new world was Philip Martinez. In 1984 Philip was hurled off his motorcycle, going at forty-five miles an hour down the San Diego freeway. He skidded across the median, landed at the foot of a concrete bridge and, getting up in a daze, he had the presence of mind to check himself for injuries. A helmet and leather jacket prevented the worst, but Philip's left arm had been severely torn near his shoulder. Like Dr. Pons's monkeys, he had a brachial avulsion—the nerves supplying his arm had been yanked off the spinal column. His left arm was completely paralyzed and lay lifeless in a sling for one year. Finally, doctors advised amputation. The arm was just getting in the way and would never regain function.

Ten years later, Philip walked into my office. Now in his midthirties, he collects a disability benefit and has made a rather impressive reputation for himself as a pool player, known among his friends as the "one-armed bandit."

Philip had heard about my experiments with phantom limbs in local press reports. He was desperate. "Dr. Ramachandran," he said, "I'm hoping you can help me." He glanced down at his missing arm. "I lost it ten years ago. But ever since I've had a terrible pain in my phantom elbow, wrist and fingers." Interviewing him further, I discovered that during the decade, Philip had never been able to move his phantom arm. It was always fixed in an awkward position. Was Philip suffering from learned paralysis? If so, could we use our virtual reality box to resurrect the phantom visually and restore movements?

I asked Philip to place his right hand on the right side of the mirror in the box and imagine that his left hand (the phantom) was on the left side. "I want you to move your right and left arms simultaneously," I instructed.

"Oh, I can't do that," said Philip. "I can move my right arm but my left arm is frozen. Every morning when I get up, I try to move my phantom because it's in this funny position and I feel that moving it might help relieve the pain. But," he said, looking down at his invisible arm, "I have never been able to generate a flicker of movement in it."

"Okay, Philip, but try anyway."

Philip rotated his body, shifting his shoulder, to "insert" his lifeless phantom into the box. Then he put his right hand on the other side of the mirror and attempted to make synchronous movements. As he gazed into the mirror, he gasped and then cried out, "Oh, my God! Oh, my God, doctor! This is unbelievable. It's mind-boggling!" He was jumping up and down like a kid. "My left arm is plugged in again. It's as if I'm in the past. All these memories from so many years ago are flooding back into my mind. I can move my arm again. I can feel my elbow moving, my wrist moving. It's all moving again."

After he calmed down a little I said, "Okay, Philip, now close your eyes."

"Oh, my," he said, clearly disappointed. "It's frozen again. I feel my right hand moving, but there's no movement in the phantom."

"Open your eyes."

"Oh, yes. Now it's moving again."

It was as though Philip had some temporary inhibition or block of the neural circuits that would ordinarily move the phantom and the visual feedback had overcome this block. More amazing still, these bodily sensations of the arm's movements were revived instantly,[3] even though they had never been felt in the preceding ten years!

Though Philip's response was exciting and provided some support for my hypothesis about learned paralysis, I went home that night and asked myself, "So what? So we have this guy moving his phantom limb again. But it's a perfectly useless ability if you think about it—precisely the sort of arcane thing that many of us medical researchers are sometimes accused of working on." I wouldn't win a prize, I realized, for getting someone to move a phantom limb.

But maybe learned paralysis is a more widespread phenomenon.[4] It might happen to people with real limbs that are paralyzed, say, from a stroke. Why do people lose the use of an arm after a stroke? When a blood vessel supplying the brain gets clogged, the fibers that extend from the front part of the brain down to the spinal cord are deprived of oxygen and sustain damage, leaving the arm paralyzed. But in the early stages of a stroke, the brain swells, temporarily causing some nerves to die off but leaving others simply stunned and "off-line," so to speak. During this time, when the arm is nonfunctional, the brain receives visual feedback: "Nope, the arm is not moving." After the swelling subsides, it's possible that the patient's brain is stuck with a form of learned paralysis. Could the mirror contraption be used to overcome at least that component of the paralysis that is due to learning? (Obviously there is nothing one can do with mirrors to restore paralysis caused by actual destruction of fibers.)

But before we could implement this kind of novel therapy for stroke patients, we needed to ensure that the effect is more than a mere temporary illusion of movement in the phantom. (Recall that when Philip closed his eyes, the sense of movement in his phantom disappeared.)

What if the patient were to practice with the box in order to receive continuous visual feedback for several days? Is it conceivable that the brain would "unlearn" its perception of damage and that movements would be permanently restored?

I went back the next day and asked Philip, "Are you willing to take this device home and practice with it?"

"Sure," said Philip. "I'd love to take it home. I find it very exciting that I can move my arm again, even if only momentarily."

So Philip took the mirror home. A week later I telephoned him. "What's happening?"

"Oh, it's fun, doctor. I use it for ten minutes every day. I put my hand inside, wave it around and see how it feels. My girlfriend and I play with it. It's very enjoyable. But when I close my eyes, it still doesn't work. And if I don't use the mirror, it doesn't work. I know you want my phantom to start moving again, but without the mirror it doesn't."

Three more weeks passed until one day Philip called me, very excited and agitated. "Doctor," he exclaimed, "it's gone!"

"What's gone?" (I thought maybe he had lost the mirror box.)

"My phantom is gone."

"What are you talking about?"

"You know, my phantom arm, which I had for ten years. It doesn't exist anymore. All I have is my phantom fingers and palm dangling from my shoulder!"

My immediate reaction was, Oh, no! I have apparently permanently altered a person's body image using a mirror. How would this affect his mental state and well-being? "Philip—does it bother you?"

"No no no no no no," he said. "On the contrary. You know the excruciating pain I always had in my elbow? The pain that tortured me several times a week? Well, now I don't have an elbow and I don't have that pain anymore. But I still have my fingers dangling from my shoulder and they still hurt." He paused, apparently to let this sink in. "Unfortunately," he added, "your mirror box doesn't work anymore because my fingers are up too high. Can you change the design to eliminate my fingers?" Philip seemed to think I was some kind of magician.

I wasn't sure I could help Philip with his request, but I realized that this was probably the first example in medical history of a successful "amputation" of a phantom limb! The experiment suggests that when Philip's right parietal lobe was presented with conflicting signals—visual feedback telling him that his arm is moving again while his muscles are telling him the arm is not there—his mind resorted to a form of denial. The only way his beleaguered brain could deal with this bizarre sensory conflict was to say, "To hell with it, there is no arm!" And as a huge bonus, Philip lost the associated pain in his phantom elbow as well, for it may be impossible to experience a disembodied pain in a nonexistent phantom. It's not clear why his fingers didn't disappear, but one reason might be that they are overrepresented—like the huge lips on the Penfield map—in the somatosensory cortex and may be more difficult to deny.

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Movements and paralysis of phantom limbs are hard enough to explain, but even more puzzling is the agonizing pain that many patients experience in the phantom soon after amputation, and Philip had brought me face to face with this problem. What confluence of biological circumstances could cause pain to erupt in a nonexistent limb? There are several possibilities.

The pain could be caused by scar tissue or neuromas—little curled-up clusters or clumps of nerve tissue in the stump. Irritation of these clumps and frayed nerve endings could be interpreted by the brain as pain in the missing limb. When neuromas are removed surgically, phantom pain sometimes vanishes, at least temporarily, but then insidiously it often returns.

The pain could also result in part from remapping. Keep in mind that remapping is ordinarily modality-specific: That simply means that the sense of touch follows touch pathways, and the feeling of warmth follows warmth pathways, and so on. (As we noted, when I lightly stroke Tom's face with a Q-tip, he feels me touching his phantom. When I dribble ice water on his cheek, he feels cold on his phantom hand and when I warm up the water he feels heat in the phantom as well as on his face.) This probably means that remapping doesn't happen randomly. The fibers concerned with each sense must "know" where to go to find their appropriate targets. Thus in most people, including you, me and amputees, one does not get cross-wiring.

But imagine what might happen if a slight error were to occur during the remapping process—a tiny glitch in the blueprint—so that some of the touch input is hooked up accidentally to pain centers. The patient might experience severe pain every time regions around his face or upper arm (rather than neuromas) were brushed, even lightly. Such trivial touches could generate excruciating pain, all because a few fibers are in the wrong place, doing the wrong thing.

Abnormal remapping could also cause pain two other ways. When we experience pain, special pathways are activated simultaneously both to carry the sensation and to amplify it or dampen it down as needed. Such "volume control" (sometimes called gate control) is what allows us to modulate our responses to pain effectively in response to changing demands (which might explain why acupuncture works or why women in some cultures don't experience pain during labor). Among amputees, it's entirely possible that these volume control mechanisms have gone awry as a result of remapping—resulting in an echolike "wha wha" reverberation and amplification of pain. Second, remapping is inherently a pathological or abnormal process, at least when it occurs on a large scale, as after the loss of a limb. It's possible that the touch synapses are not quite correctly rewired and their activity could be chaotic. Higher brain centers would then interpret the abnormal pattern of input as junk, which is perceived as pain. In truth, we really don't know how the brain translates patterns of nerve activity into conscious experience, be it pain, pleasure or color.

Finally, some patients say that the pain they felt in their limbs immediately prior to amputation persists as a kind of pain memory. For example, soldiers who have grenades blow up in their hands often report that their phantom hand is in a fixed position, clenching the grenade, ready to toss it. The pain in the hand is excruciating—the same they felt the instant the grenade exploded, seared permanently in their brains. In London I once met a woman who told me she had experienced chilblains—a frostbitelike pain due to cold weather—in her thumb for several months in her childhood. The thumb later became gangrenous and was amputated. She now has a vivid phantom thumb and experiences chilblains in it every time the weather turns cold. Another woman described arthritic pain in her phantom joints. She'd had the problem before her arm was amputated but it has continued in the absence of real joints, with the pain being worse when it gets damp and cold just as it had in the real joints before amputation.

One of my medical school professors told me a story that he swore was true, the tale of another physician, an eminent cardiologist, who developed a pulsating cramp in his leg caused by Buerger's disease—a malady that produces constriction of arteries and intense, pulsing pain in the calf muscles.

Despite many attempts at treatment, nothing eased the pain. Out of sheer despair, the physician decided to have his leg amputated. He simply couldn't live with the pain any longer. He consulted a surgeon colleague and scheduled the operation, but to the surgeon's astonishment, he said he had a special request: "After you amputate my leg, could you please pickle it in a jar of formaldehyde and give it to me?" This was eccentric, to say the least, but the surgeon agreed, amputated the leg, put it in a jar of preservative and gave it to the physician, who then put it in his office and said, "Hah, at last, I can look at this leg and laugh at it and say, 'I finally got rid of you!' "

But the leg had the last laugh. The pulsatile pains returned with a vengeance in the phantom leg. The good doctor stared at his floating limb in disbelief while it stared back at him, as if to mock all his efforts to rid himself of it.

There are many such stories in circulation, illustrating the astonishing specificity of pain memories and their tendency to surface when a limb is amputated. If this is the case, one can imagine being able to reduce the incidence of pain after amputation simply by injecting the limb with a local anesthetic before surgery. (This has been tried with some success.)

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Pain is one of the most poorly understood of all sensory experiences. It is a source of great frustration to patient and physician alike and can emerge in many different guises. One especially enigmatic complaint frequently heard from patients is that every now and then the phantom hand becomes curled into a tight, white-knuckled fist, fingers digging into palm with all the fury of a prizefighter ready to deliver a knockout blow.

Robert Townsend is an intelligent, fifty-five-year-old engineer whose cancer caused him to lose his left arm six inches above the elbow. When I saw him seven months after the amputation, he was experiencing a vivid phantom limb that would often go into an involuntary clenching spasm. "It's like my nails are digging into my phantom hand," said Robert. "The pain is unbearable." Even if he concentrated all his attention on it, he could not open his invisible hand to relieve the spasm.

We wondered whether using the mirror box could help Robert eliminate his spasms. Like Philip, Robert looked into the box, positioned his good hand to superimpose its reflection over his phantom hand and, after making a fist with the normal hand, tried to unclench both hands simultaneously. The first time he did this, Robert exclaimed that he could feel the phantom fist open along with his good fist, simply as a result of the visual feedback. Better yet, the pain disappeared. The phantom then remained unclenched for several hours until a new spasm occurred spontaneously. Without the mirror, his phantom would throb in pain for forty minutes or more. Robert took the box home and tried the same trick each time that the clenching spasm recurred. If he did not use the box, he could not unclench his fist despite trying with all his might. If he used the mirror, the hand opened instantly.

We have tried this treatment in over a dozen patients and it works for half of them. They take the mirrored box home and whenever a spasm occurs, they put their good hand into the box and open it and the spasm is eliminated. But is it a cure? It's difficult to know. Pain is notoriously susceptible to the placebo effect (the power of suggestion). Perhaps the elaborate laboratory setting or the mere presence of a charismatic expert on phantom limbs is all you need in order to eliminate the pain and it has nothing to do with mirrors. We tested this possibility on one patient by giving him a harmless battery pack that generates an electric current. Whenever the spasms and abnormal postures occurred, he was asked to rotate the dial on the unit of his "transcutaneous electrical simulator" until he began to feel a tingling in his left arm (which was his good arm). We told him that this would immediately restore voluntary movements in the phantom and provide relief from the spasms. We also told him that the procedure had worked on other patients in his predicament.

He said, "Really? Wow, I can't wait to try it."

Two days later he was back, obviously annoyed. "It's useless," he exclaimed. "I tried it five times and it just doesn't work. I turned it up to full strength even though you told me not to."

When I gave him the mirror to try that same afternoon, he was able to open his phantom hand instantly. The spasms were eliminated and so too was the "digging sensation" of nails biting into his palm. This is a mind-boggling observation if you think about it. Here is a man with no hand and no fingernails. How does one get nonexistent nails digging into a nonexistent palm, resulting in severe pain? Why would a mirror eliminate the phantom spasm?

Consider what happens in your brain when motor commands are sent from the premotor and motor cortex to make a fist. Once your hand is clenched, feedback signals from muscles and joints of your hand are sent back through the spinal cord to your brain saying, Slow down, enough. Any more pressure and it could hurt. This proprioceptive feedback applies brakes, automatically, with astonishing speed and precision.

If the limb is missing, however, this damping feedback is not possible. The brain therefore keeps sending the message, Clench more, clench more. Motor output is amplified even further (to a level that far exceeds anything you or I would ever experience) and the overflow or "sense of effort" may itself be experienced as pain. The mirror may work by providing visual feedback to unclench the hand, so that the clenching spasm is abolished.

But why the sensation of digging fingernails? Just think of the numerous occasions when you actually clenched your fist and felt your nails biting in your palm. These occasions must have created a memory link in your brain (psychologists call it a Hebbian link) between the motor command to clench and the unmistakable sensation of "nails digging," so you can readily summon up this image in your mind. Yet even though you can imagine the image quite vividly, you don't actually feel the sensation and say, "Ouch, that hurts." Why not? The reason, I believe, is that you have a real palm and the skin on the palm says there is no pain. You can imagine it but you don't feel it because you have a normal hand sending real feedback and in the clash between reality and illusion, reality usually wins.

But the amputee doesn't have a palm. There are no countermanding signals from the palm to forbid the emergence of these stored pain memories. When Robert imagines that his nails are digging into his hand, he doesn't get contradictory signals from his skin surface saying, "Robert, you fool, there's no pain down here." Indeed, if the motor commands themselves are linked to the sense of nail digging, it's conceivable that the amplification of these commands leads to a corresponding amplification of the associated pain signals. This might explain why the pain is so brutal.

The implications are radical. Even fleeting sensory associations such as the one between clenching our hands and digging our fingernails into our palms are laid down as permanent traces in the brain and are only unmasked under certain circumstances—experienced in this case as phantom limb pain. Moreover, these ideas imply that pain is an *opinion* on the organism's state of health rather than a mere reflexive response to an injury. There is no direct hotline from pain receptors to "pain centers" in the brain. On the contrary, there is so much interaction between different brain centers, like those concerned with vision and touch, that even the mere visual appearance of an opening fist can actually feed all the way back into the patient's motor and touch pathways, allowing him to feel the fist opening, thereby killing an illusory pain in a nonexistent hand.

If pain is an illusion, how much influence do senses like vision have over our subjective experiences? To find out, I tried a somewhat diabolical experiment on two of my patients. When Mary came into the lab, I asked her to place her phantom right hand, palm down, into the mirror box. I then asked her to put a gray glove on her good left hand and place it in the other side of the box, in a mirror image position. After making sure she was comfortable I instructed one of my graduate students to hide under the curtained table and put his gloved left hand into the same side of the box where Mary's good hand rested, above hers on a false platform. When Mary looked into the box she could see not only the student's gloved left hand (which looked exactly like her own left hand) but also its reflection in the mirror, as if she were looking at her own phantom right hand wearing a glove. When the student now made a fist or used his index finger pad to touch the ball of his thumb, Mary felt her phantom moving vividly. As in our previous two patients, vision was enough to trick her brain into experiencing movements in her phantom limb.

What would happen if we fooled Mary into thinking that her fingers were occupying anatomically impossible positions? The box permitted this illusion. Again, Mary put her phantom right hand, palm down, in the box. But the student now did something different. Instead of placing his left hand into the other side of the box, in an exact mirror image of the phantom, he inserted his right hand, palm up. Since the hand was gloved, it looked exactly like her "palm-down" phantom right hand. Then the student flexed his index finger to touch his palm. To Mary, peering into the box, it appeared as if her phantom index finger were bending backward to touch the back of her wrist—in the wrong direction![5] What would her reaction be?

When Mary saw her finger twisted backward, she said, "One would have thought it should feel peculiar, doctor, but it doesn't. It feels exactly like the finger is bending backward, like it isn't supposed to. But it doesn't feel peculiar or painful or anything like that."

Another subject, Karen, winced and said that the twisted phantom finger hurt. "It felt like somebody was grabbing and pulling my finger. I felt a twinge of pain," she said.

These experiments are important because they flatly contradict the theory that the brain consists of a number of autonomous modules acting as a bucket brigade. Popularized by artificial intelligence researchers, the idea that the brain behaves like a computer, with each module performing a highly specialized job and sending its output to the next module, is widely believed. In this view, sensory processing involves a one-way cascade of information sensory receptors on the skin and other sense organs to higher brain centers.

But my experiments with these patients have taught me that this is not how the brain works. Its connections are extraordinarily labile and dynamic. Perceptions emerge as a result of reverberations of signals between different levels of the sensory hierarchy, indeed even across different senses. The fact that visual input can eliminate the spasm of a nonexistent arm and then erase the associated memory of pain vividly illustrates how extensive and profound these interactions can be.

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Studying patients with phantom limbs has given me insights into the inner working of the brain that go far beyond the simple questions I started with four years ago when Tom first walked into my office. We've actually witnessed (directly and indirectly) how new connections emerge in the adult brain, how information from different senses interacts, how the activity of sensory maps is related to sensory experience and more generally how the brain is continuously updating its model of reality in response to novel sensory inputs.

This last observation sheds new light on the so-called nature versus nurture debate by allowing us to ask the question, Do phantom limbs arise mainly from nongenetic factors such as remapping or stump neuromas, or do they represent the ghostly persistence of an inborn, genetically specified "body image"? The answer seems to be that the phantom emerges from a complex interaction between the two. I'll give you five examples to illustrate this.

In the case of below-the-elbow amputees, surgeons will sometimes cleave the stump into a lobster claw–like appendage, as an alternative to a standard metal hook. After the surgery, people learn to use their pincers at the stump to grasp objects, turn them around and otherwise manipulate the material world. Intriguingly, their phantom hand (some inches away from real flesh) also feels split in two—with one or more phantom fingers occupying each pincer, vividly mimicking the movements of the appendage. I know of one instance in which a patient underwent amputation of his pincers only to be left with a permanently cleaved phantom—striking evidence that a surgeon's scalpel can dissect a phantom.

After the original surgery in which the stump was split, this patient's brain must have reshaped his body image to include the two pincers—for why else would he experience phantom pincers?

The other two stories both entertain and inform. A girl who was born without forearms and who experienced phantom hands six inches below her stumps frequently used her *phantom* fingers to calculate and solve arithmetic problems. A sixteen-year-old girl who was born with her right leg two inches shorter than her left leg and who received a below-knee amputation at age six had the odd sensation of possessing four feet! In addition to one good foot and the expected phantom foot, she developed two supernumerary phantom feet, one at the exact level of amputation and a second one, complete with calf, extending all the way down to the floor, where it should be had the limb not been congenitally shorter.[6] Although researchers have used this example to illustrate the role of genetic factors in determining body image, one could equally use it to emphasize nongenetic influences, for why would your genes specify three separate images of one leg?

A fourth example that illustrates the complex interplay between genes and environment harks back to our observation that many amputees experience vivid phantom movements, both voluntary and involuntary, but in most the movements disappear eventually. Such movements are experienced at first because the brain continues sending motor commands to the missing limb (and monitors them) after amputation. But sooner or later, the lack of visual confirmation (Gee, there is no arm) causes the patient's brain to reject these signals and the movements are no longer experienced. But if this explanation is correct, how can we understand the continued presence of vivid limb movements in people like Mirabelle, who was born without arms? I can only guess that a normal adult has had a lifetime of visual and kinesthetic feedback, a process that leads the brain to expect such feedback even after amputation. The brain is "disappointed" if the expectation is not fulfilled—leading eventually to a loss of voluntary movements or even a complete loss of the phantom itself. The sensory areas of Mirabelle's brain, however, have never received such feedback. Consequently, there is no learned dependence on sensory feedback, and that lack might explain why the sensation of movements had persisted, unchanged, for twenty-five years.

The final example comes from my own country, India, which I visit every year. The dreaded disease leprosy is still quite common there and often leads to progressive mutilation and loss of limbs. At the leprosarium at Vellore, I was told that these patients who lose their arms do not experience phantoms, and I personally saw several cases and verified these claims. The standard explanation is that the patient gradually "learns" to assimilate the stump into his body image by using visual feedback, but if this is true, how does it account for the continued presence of phantoms in amputees? Perhaps the *gradual* loss of the limb or the simultaneous presence of progressive nerve damage caused by the leprosy bacterium is somehow critical. This might allow their brains more time to readjust their body image to match reality. Odder still, when such a patient develops gangrene in his stump and the diseased tissue is amputated, he *does* develop a phantom. But it's not a phantom of the old stump; it's a phantom of the entire hand! It's as though the brain has a dual representation, one of the original body image laid down genetically and one ongoing, up-to-date image that can incorporate subsequent changes. For some weird reason, the amputation disturbs the equilibrium and resurrects the original body image, which has always been competing for attention.[7]

I mention these bizarre examples because they imply that phantom limbs emerge from a complex interplay of both genetic and experiential variables whose relative contributions can be disentangled only by systematic empirical investigations. As with most nature/nurture debates, asking which is the more important variable is meaningless—despite extravagant claims to the contrary in the IQ literature. (Indeed, the question is no more meaningful than asking whether the wetness of water results mainly from the hydrogen molecules or from the oxygen molecules that constitute H_2O!) But the good news is that by doing the right kinds of experiments, you can begin to tease them apart, investigate how they interact and eventually help develop new treatments for phantom pain. It seems extraordinary even to contemplate the possibility that you could use a visual illusion to eliminate pain, but bear in mind that pain itself is an illusion—constructed entirely in your brain like any other sensory experience. Using one illusion to erase another doesn't seem very surprising after all.

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The experiments I've discussed so far have helped us understand what is going on in the brains of patients with phantoms and given us hints as to how we might help alleviate their pain. But there is a deeper message here: *Your own body* is a phantom, one that your brain has temporarily constructed purely for convenience. I know this sounds astonishing so I will demonstrate to you the malleability of your own body image and how you can alter it profoundly in just a few seconds. Two of these experiments you can do on yourself right now, but the third requires a visit to a Halloween supply shop.

To experience the first illusion, you'll need two helpers. (I will call them Julie and Mina.) Sit in a chair, blindfolded, and ask Julie to sit on another chair in front of you, facing the same direction as you are. Have Mina stand on your right side and give her the following instructions: "Take my right hand and guide my index finger to Julia's nose. Move my hand in a rhythmic manner so that my index finger repeatedly strokes and taps her nose in a random sequence like a Morse code. At the same time, use your left hand to stroke my nose with the same rhythm and timing. The stroking and tapping of my nose and Julia's nose should be in perfect synchrony."

After thirty or forty seconds, if you're lucky, you will develop the uncanny illusion that you are touching your nose out there or that your nose has been dislocated and stretched out about three feet in front of your face. The more random and unpredictable the stroking sequence, the more striking the illusion will be. This is an extraordinary illusion; why does it happen? I suggest that your brain "notices" that the tapping and stroking sensations from your right index finger are perfectly synchronized with the strokes and taps felt on your nose. It then says, "The tapping on my nose is identical to the sensations on my right index finger; why are the two sequences identical? The likelihood that this is a coincidence is zero, and therefore the most probable explanation is that my finger must be tapping my nose. But I also know that my hand is two feet away from my face. So it follows that my nose must also be out there, two feet away."[8]

I have tried this experiment on twenty people and it works on about half of them (I hope it will work on you). But to me, the astonishing thing is that it works at all—that your certain knowledge that you have a normal nose, your image of your body and face constructed over a lifetime should be negated by just a few seconds of the right kind of sensory stimulation. This simple experiment not only shows how malleable your body image is but also illustrates the single most important principle underlying all of perception—that the mechanisms of perception are mainly involved in extracting statistical correlations from the world to create a model that is temporarily useful.

The second illusion requires one helper and is even spookier.[9] You'll need to go to a novelty or Halloween store to buy a dummy rubber hand. Then construct a two-foot by two-foot cardboard "wall" and place it on a table in front of you. Put your right hand behind the cardboard so that you cannot see it and put the dummy hand in front of the cardboard so you can see it clearly. Next have your friend stroke identical locations on both your hand and the dummy hand synchronously while you look at the dummy. Within seconds you will experience the stroking sensation as arising from the dummy hand. The experience is uncanny, for you know perfectly well that you're looking at a disembodied rubber hand, but this doesn't prevent your brain from assigning sensation to it. The illusion illustrates, once again, how ephemeral your body image is and how easily it can be manipulated.

Projecting your sensations on to a dummy hand is surprising enough, but, more remarkably, my student Rick Stoddard and I discovered that you can even experience touch sensations as arising from tables and chairs that bear no physical resemblance to human body parts. This experiment is especially easy to do since all you need is a single friend to assist you. Sit at your writing desk and hide your left hand under the table. Ask your friend to tap and stroke the surface of the table with his right hand (as you watch) and then use his hand simultaneously to stroke and tap your left hand, which is hidden from view. It is absolutely critical that you not see the movements of his left hand as this will ruin the effect (use a cardboard partition or a curtain if necessary). After a minute or so, you will start experiencing taps and strokes as emerging from the table surface even though your conscious mind knows perfectly well that this is logically absurd. Again, the sheer statistical improbability of the two sequences of taps and strokes—one seen on the table surface and one felt on your hand—lead the brain to conclude that the table is now part of your body. The illusion is so compelling that on the few occasions when I accidentally made a much longer stroke on the table surface than on the subject's hidden hand, the person exclaimed that his hand felt "lengthened" or "stretched" to absurd proportions.

Both these illusions are much more than amusing party tricks to try on your friends. The idea that you can actually *project* your sensations to external objects is radical and reminds me of phenomena such as out-of-body experiences or even voodoo (prick the doll and "feel" the pain). But how can we be sure the student volunteer isn't just being metaphorical when she says "I feel my nose out there" or "The table feels like my own hand." After all, I often have the experience of "feeling" that my car is part of my extended body image, so much so that I become infuriated if someone makes a small dent on it. But would I want to argue from this that the car had become part of my body?

These are not easy questions to tackle, but to find out whether the students really identified with the table surface, we devised a simple experiment that takes advantage of what is called the galvanic skin response or GSR. If I hit you with a hammer or hold a heavy rock over your foot and threaten to drop it, your brain's visual areas will dispatch messages to your limbic system (the emotional center) to prepare your body to take emergency measures (basically telling you to run from danger). Your heart starts pumping more blood and you begin sweating to dissipate heat. This alarm response can be monitored by measuring the changes in skin resistance—the so-called GSR—caused by the sweat. If you look at a pig, a newspaper or a pen there is no GSR, but if you look at something evocative—a Mapplethorpe photo, a *Playboy* centerfold or a heavy rock teetering above your foot—you will register a huge GSR.

So I hooked up the student volunteers to a GSR device while they stared at the table. I then stroked the hidden hand and the table surface simultaneously for several seconds until the student started experiencing the table as his own hand. Next I bashed the table surface with a hammer as the student watched. Instantly, there was a huge change in GSR as if I had smashed the student's own fingers. (When I tried the control experiment of stroking the table and hand out of sync, the subject did not experience the illusion and there was no GSR response.) It was as though the table had now become coupled to the student's own limbic system and been assimilated into his body image, so much so that pain and threat to the dummy are felt as threats to his own body, as shown by the GSR. If this argument is correct, then perhaps it's not all that silly to ask whether you identify with your car. Just punch it to see whether your GSR changes. Indeed the technique may give us a handle on elusive psychological phenomena such as the empathy and love that you feel for a child or spouse. If you are deeply in love with someone, is it possible that you have actually become part of that person? Perhaps your souls—and not merely your bodies—have become intertwined.

Now just think about what all this means. For your entire life, you've been walking around assuming that your "self" is anchored to a single body that remains stable and permanent at least until death. Indeed, the "loyalty" of your self to your own body is so axiomatic that you never even pause to think about it, let alone question it. Yet these experiments suggest the exact opposite—that your body image, despite all its appearance of durability, is an entirely transitory internal construct that can be profoundly modified with just a few simple tricks. It is merely a shell that you've temporarily created for successfully passing on your genes to your offspring.