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A Woman Perpetually Falling . . .

Rescued by the Man Who Discovered the Plasticity of Our Senses

And they saw the voices.
Exodus 20:18

Cheryl Schiltz feels like she's perpetually falling. And because she feels like she's falling, she falls.

When she stands up without support, she looks, within moments, as if she were standing on a precipice, about to plummet. First her head wobbles and tilts to one side, and her arms reach out to try to stabilize her stance. Soon her whole body is moving chaotically back and forth, and she looks like a person walking a tightrope in that frantic seesaw moment before losing his balance—except that both her feet are firmly planted on the ground, wide apart. She doesn't look like she is only afraid of falling, more like she's afraid of being pushed.

"You look like a person teetering on a bridge," I say.

"Yeah, I feel I am going to jump, even though I don't want to."

Watching her more closely, I can see that as she tries to stand still, she jerks, as though an invisible gang of hoodlums were pushing and shoving her, first from one side, then from another, cruelly trying to knock her over. Only this gang is actually inside her and has been doing this to her for five years. When she tries to walk, she has to hold on to a wall, and still she staggers like a drunk.

For Cheryl there is no peace, even after she's fallen to the floor.

"What do you feel when you've fallen?" I ask her. "Does the sense of falling go away once you've landed?"

"There have been times," says Cheryl, "when I literally lose the sense of the feeling of the floor . . . and an imaginary trapdoor opens up and swallows me." Even when she has fallen, she feels she is still falling, perpetually, into an infinite abyss.

Cheryl's problem is that her vestibular apparatus, the sensory organ for the balance system, isn't working. She is very tired, and her sense that she is in free fall is driving her crazy because she can't think about anything else. She fears the future. Soon after her problem began, she lost her job as an international sales representative and now lives on a disability check of $1,000 a month. She has a newfound fear of growing old. And she has a rare form of anxiety that has no name.

An unspoken and yet profound aspect of our well-being is based on having a normally functioning sense of balance. In the 1930s the psychiatrist Paul Schilder studied how a healthy sense of being and a "stable" body image are related to the vestibular sense. When we talk of "feeling settled" or "unsettled," "balanced" or "unbalanced," "rooted" or "rootless," "grounded" or "ungrounded," we are speaking a vestibular language, the truth of which is fully apparent only in people like Cheryl. Not surprisingly, people with her disorder often fall to pieces psychologically, and many have committed suicide.

We have senses we don't know we have—until we lose them; balance is one that normally works so well, so seamlessly, that it is not listed among the five that Aristotle described and was overlooked for centuries afterward.

The balance system gives us our sense of orientation in space. Its sense organ, the vestibular apparatus, consists of three semicircular canals in the inner ear that tell us when we are upright and how gravity is affecting our bodies by detecting motion in three-dimensional space. One canal detects movement in the horizontal plane, another in the vertical plane, and another when we are moving forward or backward. The semicircular canals contain little hairs in a fluid bath. When we move our head, the fluid stirs the hairs, which send a signal to our brains telling us that we have increased our velocity in a particular direction. Each movement requires a corresponding adjustment of the rest of the body. If we move our heads forward, our brains tell an appropriate segment of our bodies to adjust, unconsciously, so that we can offset that change in our center of gravity and maintain our balance. The signals from the vestibular apparatus go along a nerve to a specialized clump of neurons in our brain, called the "vestibular nuclei," which process them, then send commands to our muscles to adjust themselves. A healthy vestibular apparatus also has a strong link to our visual system. When you run after a bus, with your head bouncing up and down as you race forward, you are able to keep that moving bus at the center of your gaze because your vestibular apparatus sends messages to your brain, telling it the speed and direction in which you are running. These signals allow your brain to rotate and adjust the position of your eyeballs to keep them directed at your target, the bus.

I am with Cheryl, and Paul Bach-y-Rita, one of the great pioneers in understanding brain plasticity, and his team, in one of his labs. Cheryl is hopeful about today's experiment and is stoical but open about her condition. Yuri Danilov, the team biophysicist, does the calculations on the data they are gathering on Cheryl's vestibular system. He is Russian, extremely smart, and has a deep accent. He says, "Cheryl is patient who has lost vestibular system—ninety-five to one hundred percent."

By any conventional standard, Cheryl's case is a hopeless one. The conventional view sees the brain as made up of a group of specialized processing modules, genetically hardwired to perform specific functions and those alone, each developed and refined over millions of years of evolution. Once one of them is this damaged, it can't be replaced. Now that her vestibular system is damaged, Cheryl has as much chance of regaining her balance as a person whose retina has been damaged has of seeing again.

But today all that is about to be challenged.

She is wearing a construction hat with holes in the side and a device inside it called an accelerometer. Licking a thin plastic strip with small electrodes on it, she places it on her tongue. The accelerometer in the hat sends signals to the strip, and both are attached to a nearby computer. She laughs at the way she looks in the hat, "because if I don't laugh I will cry."

This machine is one of Bach-y-Rita's bizarre-looking prototypes. It will replace her vestibular apparatus and send balance signals to her brain from her tongue. The hat may reverse Cheryl's current nightmare. In 1997 after a routine hysterectomy, Cheryl, then thirty-nine years old, got a postoperative infection and was given the antibiotic gentamicin. Excessive use of gentamicin is known to poison the inner ear structures and can be responsible for hearing loss (which Cheryl doesn't have), ringing in the ears (which she does), and devastation to the balance system. But because gentamicin is cheap and effective, it is still prescribed, though usually for only a brief period of time. Cheryl says she was given the drug way beyond the limit. And so she became one of a small tribe of gentamicin's casualties, known among themselves as Wobblers.

Suddenly one day she discovered she couldn't stand without falling. She'd turn her head, and the whole room would move. She

couldn't figure out if she or the walls were causing the movement. Finally she got to her feet by hanging on to the wall and reached for the phone to call her doctor.

When she arrived at the hospital, the doctors gave her various tests to see if her vestibular function was working. They poured freezing-cold and warm water into her ears and tilted her on a table. When they asked her to stand with her eyes closed, she fell over. A doctor told her, "You have no vestibular function." The tests showed she had about 2 percent of the function left.

"He was," she says, "so nonchalant. 'It looks like a side effect of the gentamicin.' " Here Cheryl gets emotional. "Why in the world wasn't I told about that? 'It's permanent,' he said. I was alone. My mother had taken me to the doctor, but she went off to get the car and was waiting for me outside the hospital. My mother asked, 'Is it going to be okay?' And I looked at her and said, 'It's permanent . . . this is never going to go away.' "

Because the link between Cheryl's vestibular apparatus and her visual system is damaged, her eyes can't follow a moving target smoothly. "Everything I see bounces like a bad amateur video," she says. "It's as though everything I look at seems made of Jell-O, and with each step I take, everything wiggles."

Although she can't track moving objects with her eyes, her vision is all she has to tell her that she is upright. Our eyes help us know where we are in space by fixing on horizontal lines. Once when the lights went out, Cheryl immediately fell to the floor. But vision proves an unreliable crutch for her, because any kind of movement in front of her—even a person reaching out to her—exacerbates the falling feeling. Even zigzags on a carpet can topple her, by initiating a burst of false messages that make her think she's standing crookedly when she's not.

She suffers mental fatigue, as well, from being on constant high alert. It takes a lot of brain power to maintain an upright position—brain power that is taken away from such mental functions as memory and the ability to calculate and reason.

While Yuri is readying the computer for Cheryl, I ask to try the machine. I put on the construction worker's hat and slip into my mouth the plastic device with electrodes on it, called a tongue display. It is flat, no thicker than a stick of chewing gum.

The accelerometer, or sensor, in the hat detects movement in two planes. As I nod my head, the movement is translated onto a map on the computer screen that permits the team to monitor it. The same map is projected onto a small array of 144 electrodes implanted in the plastic strip on my tongue. As I tilt forward, electric shocks that feel like champagne bubbles go off on the front of my tongue, telling me that I am bending forward. On the computer screen I can see where my head is. As I tilt back, I feel the champagne swirl in a gentle wave to the back of my tongue. The same happens when I tilt to the sides. Then I close my eyes and experiment with finding my way in space with my tongue. I soon forget that the sensory information is coming from my tongue and can read where I am in space.

Cheryl takes the hat back; she keeps her balance by leaning against the table.

"Let's begin," says Yuri, adjusting the controls.

Cheryl puts on the hat and closes her eyes. She leans back from the table, keeping two fingers on it for contact. She doesn't fall, though she has no indication whatsoever of what is up and down except the swirling of the champagne bubbles over her tongue. She lifts her fingers from the table. She's not wobbling anymore. She starts to cry—the flood of tears that comes after a trauma; she can open up now that she has the hat on and feels safe. The first time she put on the hat, the sense of perpetual falling left her—for the first time in five years. Her goal today is to stand, free, for twenty minutes, with the hat on, trying to keep centered. For anyone—not to mention a Wobbler—to stand straight for twenty minutes requires the training and skill of a guard at Buckingham Palace.

She looks peaceful. She makes minor corrections. The jerking has stopped, and the mysterious demons that seemed to be inside her, pushing her, shoving her, have vanished. Her brain is decoding signals from her artificial vestibular apparatus. For her, these moments of peace are a miracle—a neuroplastic miracle, because somehow these tingling sensations on her tongue, which normally make their way to the part of the brain called the sensory cortex—the thin layer on the surface of the brain that processes the sense of touch—are making their way, through a novel pathway in the brain, to the brain area that processes balance.

"We are now working on getting this device small enough so that it is hidden in the mouth," says Bach-y-Rita, "like an orthodontist's mouth retainer. That's our goal. Then she, and anyone with this problem, will have a normal life restored. Someone like Cheryl should be able to wear the apparatus, talk, and eat without anyone knowing she has it.

"But this isn't just going to affect people damaged by gentamicin," he continues. "There was an article in *The New York Times* yesterday on falls in the elderly. Old people are more frightened of falling than of being mugged. A third of the elderly fall, and because they fear falling, they stay home, don't use their limbs, and become more physically frail. But I think part of the problem is that the vestibular sense—just like hearing, taste, eyesight, and our other senses—starts to weaken as we age. This device will help them."

"It's time," says Yuri, turning off the machine.

Now comes the second neuroplastic marvel. Cheryl removes the tongue device and takes off the hat. She gives a big grin, stands free with her eyes closed, and doesn't fall. Then she opens her eyes and, still not touching the table, lifts one foot off the ground, so she's balancing on the other.

"I love this guy," she says, and goes over and gives Bach-y-Rita a hug. She comes over to me. She's overflowing with emotion, overwhelmed by feeling the world under her feet again, and she gives me a hug too.

"I feel anchored and solid. I don't have to think where my muscles are. I can actually think of other things." She returns to Yuri and gives him a kiss.

"I have to emphasize why this is a miracle," says Yuri, who considers himself a data-driven skeptic. "She has almost no natural sensors. For the past twenty minutes we provided her with an artificial sensor. But the real miracle is what is happening *now* that we have removed the device, and she doesn't have either an artificial or a natural vestibular apparatus. We are awakening some kind of force inside her."

The first time they tried the hat, Cheryl wore it for only a minute. They noticed that after she took it off, there was a "residual effect" that lasted about twenty seconds, a third of the time she wore the device. Then Cheryl wore the hat for two minutes and the residual effect lasted about forty seconds. Then they went up to about twenty minutes, expecting a residual effect of just under seven minutes. But instead of lasting a third of the time, it lasted triple the time, a full hour. Today, Bach-y-Rita says, they are experimenting to see if twenty more minutes on the device will lead to some kind of training effect, so that the residual effect will last even longer.

Cheryl starts clowning and showing off. "I can walk like a woman again. That's probably not important to most people, but it means a lot that I don't have to walk with my feet wide apart now."

She gets up on a chair and jumps off. She bends down to pick things up off the floor, to show she can right herself. "Last time I did this I was able to jump rope in the residual time."

"What is amazing," says Yuri, "is that she doesn't just keep her posture. After some time on the device, she behaves almost normally. Balancing on a beam. Driving a car. It is the recovery of the vestibular function. When she moves her head, she can keep her focus on her target—the link between the visual and vestibular systems is also recovered."

I look up, and Cheryl is dancing with Bach-y-Rita.
She leads.

How is it that Cheryl can dance and has returned to normal functioning without the machine? Bach-y-Rita thinks there are several reasons. For one, her damaged vestibular system is disorganized and "noisy," sending off random signals. Thus, noise from the damaged tissue blocks any signals sent by healthy tissue. The machine helps to reinforce the signals from her healthy tissues. He thinks the machine also helps recruit other pathways, which is where plasticity comes in. A brain system is made of many neuronal pathways, or neurons that are connected to one another and working together. If certain key pathways are blocked, then the brain uses older pathways to go around them. "I look at it this way," says Bach-y-Rita. "If you are driving from here to Milwaukee, and the main bridge goes out, first you are paralyzed. Then you take old secondary roads through the farmland. Then, as you use these roads more, you find shorter paths to use to get where you want to go, and you start to get there faster." These "secondary" neural pathways are "unmasked," or exposed, and, with use, strengthened. This "unmasking" is generally thought to be one of the main ways the plastic brain reorganizes itself.

The fact that Cheryl is gradually lengthening the residual effect suggests that the unmasked pathway is getting stronger. Bach-y-Rita hopes that Cheryl, with training, will be able to continue extending the length of the residual effect.

A few days later an e-mail for Bach-y-Rita arrives from Cheryl, her report from home about how long the residual time lasted. "Total residual time was: 3 hours, 20 minutes . . . The wobbling begins in my head—just like usual . . . I am having trouble finding words . . . Swimming feeling in my head. Tired, exhausted . . . Depressed."

A painful Cinderella story. Coming down from normalcy is very hard. When it happens, she feels she has died, come to life, and then died again. On the other hand, three hours and twenty minutes after only twenty minutes on the machine is residual time ten times greater than the time on the device. She is the first Wobbler ever to have been treated, and even if the residual time never grows longer, she could now wear the device briefly four times a day and have a normal life. But there is good reason to expect more, since each session seems to be training her brain to extend the residual time. If this keeps up . . .

. . . It did keep up. Over the next year Cheryl wore the device more frequently to get relief and build up her residual effect. Her residual effect progressed to multiple hours, to days, and then to four months. Now she does not use the device at all and no longer considers herself a Wobbler.

In 1969, *Nature,* Europe's premier science journal, published a short article that had a distinctly sci-fi feel about it. Its lead author, Paul Bach-y-Rita, was both a basic scientist and a rehabilitation physician—a rare combination. The article described a device that enabled people who had been blind from birth to see. All had damaged retinas and had been considered completely untreatable.

The *Nature* article was reported in *The New York Times, Newsweek,* and *Life,* but perhaps because the claim seemed so implausible, the device and its inventor soon slipped into relative obscurity.

Accompanying the article was a picture of a bizarre-looking machine—a large old dentist's chair with a vibrating back, a tangle of wires, and bulky computers. The whole contraption, made of castaway parts combined with 1960s electronics, weighed four hundred pounds.

A congenitally blind person—someone who had never had any experience of sight—sat in the chair, behind a large camera the size of those used in television studios at the time. He "scanned" a scene in front of him by turning hand cranks to move the camera, which sent electrical signals of the image to a computer that processed them. Then the electrical signals were conveyed to four hundred vibrating stimulators, arranged in rows on a metal plate attached to the inside of the chair back, so the stimulators rested against the blind subject's skin. The stimulators functioned like pixels vibrating for the dark part of a scene and holding still for the brighter shades. This "tactile-vision device," as it was called, enabled blind subjects to read, make out faces and shadows, and distinguish which objects were closer and which farther away. It allowed them to discover perspective and observe how objects seem to change shape depending upon the angle from which they were viewed. The six subjects of the experiment learned to recognize such objects as a telephone, even when it was partially obscured by a vase. This being the 1960s, they even learned to recognize a picture of the anorexic supermodel Twiggy.

Everyone who used the relatively clunky tactile-vision device had a remarkable perceptual experience, as they went from having tactile sensations to "seeing" people and objects.

With a little practice, the blind subjects began to experience the space in front of them as three-dimensional, even though the information entered from the two-dimensional array on their backs. If someone threw a ball toward the camera, the subject would automatically jump back to duck it. If the plate of vibrating stimulators was moved from their backs to their abdomens, subjects still accurately perceived the scene as happening in front of the camera. If tickled near the stimulators, they didn't confuse the tickle with a visual stimulus. Their mental perceptual experience took place not on the skin surface but in the world. And their perceptions were complex. With practice, subjects could move the camera around and say things like "That is Betty; she is wearing her hair down today and does not have her glasses on; her mouth is open, and she is moving her right hand from her left side to the back of her head." True, the resolution was often poor, but as Bach-y-Rita would explain, vision doesn't have to be perfect to be vision. "When we walk down a foggy street and see the outline of a building," he would ask, "are we seeing it any less for the lack of resolution? When we see something in black and white, are we not seeing it for lack of color?"

This now-forgotten machine was one of the first and boldest applications of neuroplasticity—an attempt to use one sense to replace another—and it worked. Yet it was thought implausible and ignored because the scientific mind-set at the time assumed that the brain's structure is fixed, and that our senses, the avenues by which experience gets into our minds, are hardwired. This idea, which still has many adherents, is called "localizationism." It's closely related to the idea that the brain is like a complex machine, made up of parts, each of which performs a specific mental function and exists in a genetically predetermined or hardwired *location*—hence the name. A brain that is hardwired, and in which each mental function has a strict location, leaves little room for plasticity.

The idea of the machinelike brain has inspired and guided neuroscience since it was first proposed in the seventeenth century, replacing more mystical notions about the soul and the body. Scientists, impressed by the discoveries of Galileo (1564–1642), who showed that the planets could be understood as inanimate bodies moved by mechanical forces, came to believe that all nature functioned as a large cosmic clock, subject to the laws of physics, and they began to explain individual living things, including our bodily organs, mechanistically, as though they too were machines. This idea that all nature was like a vast mechanism, and that our organs were machinelike, replaced the two-thousand-year-old Greek idea that viewed all nature as a vast living organism, and our bodily organs as anything but inanimate mechanisms. But the first great accomplishment of this new "mechanistic biology" was a brilliant and original achievement. William Harvey (1578–1657), who studied anatomy in Padua, Italy, where Galileo lectured, discovered how our blood circulates through our bodies and demonstrated that the heart functions like a pump, which is, of course, a simple machine. It soon seemed to many scientists that for an explanation to be scientific it had to be mechanistic—that is, subject to the mechanical laws of motion. Following Harvey, the French philosopher René Descartes (1596–1650) argued that the brain and nervous system also functioned like a pump. Our nerves were really tubes, he argued, that went from our limbs to the brain and back. He was the first person to theorize how reflexes work, proposing that when a person is touched on the skin, a fluidlike substance in the nerve tubes flows to the brain and is mechanically "reflected" back down the nerves to move the muscles. As crude as it sounds, he wasn't so far off. Scientists soon refined his primitive picture, arguing that not some fluid but an electric current moved through the nerves. Descartes's idea of the brain as a complex machine culminated in our current idea of the brain as a computer and in localizationism. Like a machine, the brain came to be seen as made of parts, each one in a preassigned location, each performing a single function, so that if one of those parts was damaged, nothing could be done to replace it; after all, machines don't grow new parts.

Localizationism was applied to the senses as well, theorizing that each of our senses—sight, hearing, taste, touch, smell, balance—has a receptor cell that specializes in detecting one of the various forms of energy around us. When stimulated, these receptor cells send an electric signal along their nerve to a specific brain area that processes that sense. Most scientists believed that these brain areas were so specialized that one area could never do the work of another.

Almost in isolation from his colleagues, Paul Bach-y-Rita rejected these localizationist claims. Our senses have an unexpectedly plastic nature, he discovered, and if one is damaged, another can sometimes take over for it, a process he calls "sensory substitution." He developed ways of triggering sensory substitution and devices that give us "supersenses." By discovering that the nervous system can adapt to seeing with cameras instead of retinas, Bach-y-Rita laid the groundwork for the greatest hope for the blind: retinal implants, which can be surgically inserted into the eye.

Unlike most scientists, who stick to one field, Bach-y-Rita has become an expert in many—medicine, psychopharmacology, ocular neurophysiology (the study of eye muscles), visual neurophysiology (the study of sight and the nervous system), and biomedical engineering. He follows ideas wherever they take him. He speaks five languages and has lived for extended periods in Italy, Germany, France, Mexico, Sweden, and throughout the United States. He has worked in the labs of major scientists and Nobel Prize winners, but he has never much cared what others thought and doesn't play the political games that many researchers do in order to get ahead. After becoming a physician, he gave up medicine and switched to basic research. He asked questions that seemed to defy common sense, such as, "Are eyes necessary for vision, or ears for hearing, tongues for tasting, noses for smelling?" And then, when he was forty-four years old, his mind ever restless, he switched back to medicine and began a medical residency, with its endless days and sleepless nights, in one of the dreariest specialties of all: rehabilitation medicine. His ambition was to turn an intellectual backwater into a science by applying to it what he had learned about plasticity.

Bach-y-Rita is a completely unassuming man. He is partial to five-dollar suits and wears Salvation Army clothes whenever his wife lets him get away with it. He drives a rusty twelve-year-old car, his wife a new model Passat.

He has a full head of thick, wavy gray hair, speaks softly and rapidly, has the darkish skin of a Mediterranean man of Spanish and Jewish ancestry, and appears a lot younger than his sixty-nine years.

He's obviously cerebral but radiates a boyish warmth toward his wife, Esther, a Mexican of Mayan descent.

He is used to being an outsider. He grew up in the Bronx, was four foot ten when he entered high school because of a mysterious disease that stunted his growth for eight years, and was twice given a preliminary diagnosis of leukemia. He was beaten up by the larger students every day and during those years developed an extraordinarily high pain threshold. When he was twelve, his appendix burst, and the mysterious disease, a rare form of chronic appendicitis, was properly diagnosed. He grew eight inches and won his first fight.

We are driving through Madison, Wisconsin, his home when he's not in Mexico. He is devoid of pretension, and after many hours of our talking together, he lets only one even remotely self-congratulatory remark leave his lips.

"I can connect anything to anything." He smiles.

"We see with our brains, not with our eyes," he says.

This claim runs counter to the commonsensical notion that we see with our eyes, hear with our ears, taste with our tongues, smell with our noses, and feel with our skin. Who would challenge such facts? But for Bach-y-Rita, our eyes merely sense changes in light energy; it is our brains that perceive and hence see.

How a sensation enters the brain is not important to Bach-y-Rita. "When a blind man uses a cane, he sweeps it back and forth, and has only one point, the tip, feeding him information through the skin receptors in the hand. Yet this sweeping allows him to sort out where the doorjamb is, or the chair, or distinguish a foot when he hits it, because it will give a little. Then he uses this information to guide himself to the chair to sit down. Though his hand sensors are where he gets the information and where the cane 'interfaces' with him, what he *subjectively* perceives is not the cane's pressure on his hand but the layout of the room: chairs, walls, feet, the three-dimensional space. The actual receptor surface in the hand becomes merely a relay for information, a data port. The receptor surface loses its identity in the process."

Bach-y-Rita determined that skin and its touch receptors could substitute for a retina, because both the skin and the retina are two-dimensional sheets, covered with sensory receptors, that allow a "picture" to form on them.

It's one thing to find a new data port, or way of getting sensations to the brain. But it's another for the brain to decode these skin sensations and turn them into pictures. To do that, the brain has to learn something new, and the part of the brain devoted to processing touch has to adapt to the new signals. This adaptability implies that the brain is plastic in the sense that it can reorganize its sensory-perceptual system.

If the brain can reorganize itself, simple localizationism cannot be a correct image of the brain. At first even Bach-y-Rita was a localizationist, moved by its brilliant accomplishments. Serious localizationism was first proposed in 1861, when Paul Broca, a surgeon, had a stroke patient who lost the ability to speak and could utter only one word. No matter what he was asked, the poor man responded, "Tan, tan." When he died, Broca dissected his brain and found damaged tissue in the left frontal lobe. Skeptics doubted that speech could be localized to a single part of the brain until Broca showed them the injured tissue, then reported on other patients who had lost the ability to speak and had damage in the same location. That place came to be called "Broca's area" and was presumed to coordinate the movements of the muscles of the lips and tongue. Soon afterward another physician, Carl Wernicke, connected damage in another brain area farther back to a different problem: the inability to understand language. Wernicke proposed that the damaged area was responsible for the mental representations of words and comprehension. It came to be known as "Wernicke's area." Over the next hundred years localizationism became more specific as new research refined the brain map.

Unfortunately, though, the case for localizationism was soon

exaggerated. It went from being a series of intriguing correlations (observations that damage to specific brain areas led to the loss of specific mental functions) to a general theory that declared that every brain function had only one hardwired location—an idea summarized by the phrase "one function, one location," meaning that if a part was damaged, the brain could not reorganize itself or recover that lost function.

A dark age for plasticity began, and any exceptions to the idea of "one function, one location" were ignored. In 1868 Jules Cotard studied children who had early massive brain disease, in which the left hemisphere (including Broca's area) wasted away. Yet these children could still speak normally. This meant that even if speech tended to be processed in the left hemisphere, as Broca claimed, the brain might be plastic enough to reorganize itself, if necessary. In 1876 Otto Soltmann removed the motor cortex from infant dogs and rabbits—the part of the brain thought to be responsible for movement—yet found they were still able to move. These findings were submerged in the wave of localizationist enthusiasm.

Bach-y-Rita came to doubt localizationism while in Germany in the early 1960s. He had joined a team that was studying how vision worked by measuring with electrodes electrical discharge from the visual processing area of a cat's brain. The team fully expected that when they showed the cat an image, the electrode in its visual processing area would send off an electric spike, showing it was processing that image. And it did. But when the cat's paw was accidentally stroked, the visual area also fired, indicating that it was processing touch as well. And they found that the visual area was also active when the cat heard sounds.

Bach-y-Rita began to think that the localizationist idea of "one function, one location" couldn't be right. The "visual" part of the cat's brain was processing at least two other functions, touch and sound. He began to conceive of much of the brain as "polysensory"—that its sensory areas were able to process signals from more than one sense.

This can happen because all our sense receptors translate different kinds of energy from the external world, no matter what the source, into electrical patterns that are sent down our nerves. These electrical patterns are the universal language "spoken" inside the brain—there are no visual images, sounds, smells, or feelings moving inside our neurons. Bach-y-Rita realized that the areas that process these electrical impulses are far more homogeneous than neuroscientists appreciated, a belief that was reinforced when the neuroscientist Vernon Mountcastle discovered that the visual, auditory, and sensory cortices all have a similar six-layer processing structure. To Bach-y-Rita, this meant that any part of the cortex should be able to process whatever electrical signals were sent to it, and that our brain modules were not so specialized after all.

Over the next few years Bach-y-Rita began to study all the exceptions to localizationism. With his knowledge of languages, he delved into the untranslated, older scientific literature and rediscovered scientific work done before the more rigid versions of localizationism had taken hold. He discovered the work of Marie-Jean-Pierre Flourens, who in the 1820s showed that the brain could reorganize itself. And he read the oft-quoted but seldom translated work of Broca in French and found that even Broca had not closed the door to plasticity as his followers had.

The success of his tactile-vision machine further inspired Bach-y-Rita to reinvent his picture of the human brain. After all, it was not his machine that was the miracle, but the brain that was alive, changing, and adapting to new kinds of artificial signals. As part of the reorganization, he guessed that signals from the sense of touch (processed initially in the sensory cortex, near the top of the brain) were rerouted to the visual cortex at the back of the brain for further processing, which meant that any neuronal paths that ran from the skin to the visual cortex were undergoing development.

Forty years ago, just when localization's empire had extended to

its farthest reaches, Bach-y-Rita began his protest. He praised localization's accomplishments but argued that "a large body of evidence indicates that the brain demonstrates both motor and sensory plasticity." One of his papers was rejected for publication six times by journals, not because the evidence was disputed but because he dared to put the word "plasticity" in the title. After his *Nature* article came out, his beloved mentor, Ragnar Granit, who had received the Nobel Prize in physiology in 1965 for his work on the retina, and who had arranged for the publication of Bach-y-Rita's medical school thesis, invited him over for tea. Granit asked his wife to leave the room and, after praising Bach-y-Rita's work on the eye muscles, asked him—for his own good—why he was wasting his time with "that adult toy." Yet Bach-y-Rita persisted and began to lay out, in a series of books and several hundred articles, the evidence for brain plasticity and to develop a theory to explain how it might work.

Bach-y-Rita's deepest interest became explaining plasticity, but he continued to invent sensory-substitution devices. He worked with engineers to shrink the dentist-chair–computer-camera device for the blind. The clumsy, heavy plate of vibrating stimulators that had been attached to the back has now been replaced by a paper-thin strip of plastic covered with electrodes, the diameter of a silver dollar, that is slipped onto the tongue. The tongue is what he calls the ideal "brain-machine interface," an excellent entry point to the brain because it has no insensitive layer of dead skin on it. The computer too has shrunk radically, and the camera that was once the size of a suitcase now can be worn strapped to the frame of eyeglasses.

He has been working on other sensory-substitution inventions as well. He received NASA funding to develop an electronic "feeling" glove for astronauts in space. Existing space gloves were so thick that it was hard for the astronauts to feel small objects or perform delicate movements. So on the outside of the glove he put electric sensors that relayed electrical signals to the hand. Then he took what he learned making the glove and invented one to help people with leprosy, whose illness mutilates the skin and destroys peripheral nerves so that the lepers lose sensation in their hands. This glove, like the astronaut's glove, had sensors on the outside, and it sent its signals to a healthy part of the skin—away from the diseased hands—where the nerves were unaffected. That healthy skin became the portal of entry for hand sensations. He then began work on a glove that would allow blind people to read computer screens, and he even has a project for a condom that he hopes will allow spinal cord injury victims who have no feeling in their penises to have orgasms. It is based on the premise that sexual excitement, like other sensory experiences, is "in the brain," so the sensations of sexual movement, picked up by sensors on the condom, can be translated into electrical impulses that can then be transmitted to the part of the brain that processes sexual excitement. Other potential uses of his work include giving people "supersenses," such as infrared or night vision. He has developed a device for the Navy SEALs that helps them sense how their bodies are oriented underwater, and another, successfully tested in France, that tells surgeons the exact position of a scalpel by sending signals from an electronic sensor attached to the scalpel to a small device attached to their tongues and to their brains.

The origin of Bach-y-Rita's understanding of brain rehabilitation lies in the dramatic recovery of his own father, the Catalan poet and scholar Pedro Bach-y-Rita, after a disabling stroke. In 1959 Pedro, then a sixty-five-year-old widower, had a stroke that paralyzed his face and half of his body and left him unable to speak.

George, Paul's brother, now a psychiatrist in California, was told that his father had no hope of recovery and would have to go into an institution. Instead, George, then a medical student in Mexico, brought his paralyzed father from New York, where he lived, back to

Mexico to live with him. At first he tried to arrange rehabilitation for his father at the American British Hospital, which offered only a typical four-week rehab, as nobody believed the brain could benefit from extended treatment. After four weeks his father was nowhere near better. He was still helpless and needed to be lifted onto and off the toilet and showered, which George did with the help of the gardener.

"Fortunately, he was a little man, a hundred and eighteen pounds, and we could manage him," says George.

George knew nothing about rehabilitation, and his ignorance turned out to be a godsend, because he succeeded by breaking all its current rules, unencumbered by pessimistic theories.

"I decided that instead of teaching my father to walk, I was going to teach him first to crawl. I said, 'You started off crawling, you are going to have to crawl again for a while.' We got kneepads for him. At first we held him on all fours, but his arms and legs didn't hold him very well, so it was a struggle." As soon as Pedro could support himself somewhat, George then got him to crawl with his weak shoulder and arm supported by a wall. "That crawling beside the wall went on for months. After that I even had him practicing in the garden, which led to problems with the neighbors, who were saying it wasn't nice, it was unseemly, to be making the professor crawl like a dog. The only model I had was how babies learn. So we played games on the floor, with me rolling marbles, and him having to catch them. Or we'd throw coins on the floor, and he'd have to try and pick them up with his weak right hand. Everything we tried involved turning normal life experiences into exercises. We turned washing pots into an exercise. He'd hold the pot with his good hand and make his weak hand—it had little control and made spastic jerking movements—go round and round, fifteen minutes clockwise, fifteen minutes counterclockwise. The circumference of the pot kept his hand contained. There were steps, each one overlapping with the one before, and little by little he got better. After a while he helped to design the steps. He wanted to get to the point where he could sit down and eat with me and the other medical students." The regime took many hours every day, but gradually Pedro went from crawling, to moving on his knees, to standing, to walking.

Pedro struggled with his speech on his own, and after about three months there were signs it too was coming back. After a number of months he wanted to resume his writing. He would sit in front of the typewriter, his middle finger over the desired key, then drop his whole arm to strike it. When he had mastered that, he would drop just the wrist, and finally the fingers, one at a time. Eventually he learned to type normally again.

At the end of a year his recovery was complete enough for Pedro, now sixty-eight, to start full-time teaching again at City College in New York. He loved it and worked until he retired at seventy. Then he got another teaching job at San Francisco State, remarried, and kept working, hiking, and traveling. He was active for seven more years after his stroke. On a visit to friends in Bogotá, Colombia, he went climbing high in the mountains. At nine thousand feet he had a heart attack and died shortly thereafter. He was seventy-two.

I asked George if he understood how unusual this recovery was so long after his father's stroke and whether he thought at the time that the recovery might have been the result of brain plasticity.

"I just saw it in terms of taking care of Papa. But Paul, in subsequent years, talked about it in terms of neuroplasticity. Not right away, though. It wasn't until after our father died."

Pedro's body was brought to San Francisco, where Paul was working. It was 1965, and in those days, before brain scans, autopsies were routine because they were one way doctors could learn about brain diseases, and about why a patient died. Paul asked Dr. Mary Jane Aguilar to perform the autopsy.

"A few days later Mary Jane called me and said, 'Paul, come down. I've got something to show you.' When I got to the old Stanford Hospital, there, spread out on the table, were slices of my father's brain on slides."

He was speechless.

"I was feeling revulsion, but I could also see Mary Jane's excitement, because what the slides showed was that my father had had a huge lesion from his stroke and that it had never healed, even though he recovered all those functions. I freaked out. I got numb. I was thinking, 'Look at all this damage he has.' And she said, 'How can you recover with all this damage?' "

When he looked closely, Paul saw that his father's seven-year-old lesion was mainly in the brain stem—the part of the brain closest to the spinal cord—and that other major brain centers in the cortex that control movement had been destroyed by the stroke as well. Ninety-seven percent of the nerves that run from the cerebral cortex to the spine were destroyed—catastrophic damage that had caused his paralysis.

"I knew that meant that somehow his brain had totally reorganized itself with the work he did with George. We didn't know how remarkable his recovery was until that moment, because we had no idea of the extent of his lesion, since there were no brain scans in those days. When people did recover, we tended to assume that there really hadn't been much damage in the first place. She wanted me to be a coauthor on the paper she wrote about his case. I couldn't."

His father's story was firsthand evidence that a "late" recovery could occur even with a massive lesion in an elderly person. But after examining that lesion and reviewing the literature, Paul found more evidence that the brain can reorganize itself to recover functions after devastating strokes, discovering that in 1915 an American psychologist, Shepherd Ivory Franz, had shown that patients who had been paralyzed for twenty years were capable of making late recoveries with brain-stimulating exercises.

His father's "late recovery" triggered a career change for Bach-y-Rita. At forty-four, he went back to practicing medicine and did residencies in neurology and rehabilitation medicine. He understood that for patients to recover they needed to be motivated, as his father had been, with exercises that closely approximated real-life activities.

He turned his attention to treating strokes, focusing on "late rehabilitation," helping people overcome major neurological problems years after they'd begun, and developing computer video games to train stroke patients to move their arms again. And he began to integrate what he knew about plasticity into exercise design. Traditional rehabilitation exercises typically ended after a few weeks, when a patient stopped improving, or "plateaued," and doctors lost the motivation to continue. But Bach-y-Rita, based on his knowledge of nerve growth, began to argue that these learning plateaus were temporary—part of a plasticity-based learning cycle—in which stages of learning are followed by periods of consolidation. Though there was no *apparent* progress in the consolidation stage, biological changes were happening internally, as new skills became more automatic and refined.

Bach-y-Rita developed a program for people with damaged facial motor nerves, who could not move their facial muscles and so couldn't close their eyes, speak properly, or express emotion, making them look like monstrous automatons. Bach-y-Rita had one of the "extra" nerves that normally goes to the tongue surgically attached to a patient's facial muscles. Then he developed a program of brain exercises to train the "tongue nerve" (and particularly the part of the brain that controls it) to act like a facial nerve. These patients learned to express normal facial emotions, speak, and close their eyes—one more instance of Bach-y-Rita's ability to "connect anything to anything."

Thirty-three years after Bach-y-Rita's *Nature* article, scientists using the small modern version of his tactile-vision machine have put patients under brain scans and confirmed that the tactile images that enter patients through their tongues are indeed processed in their brains' visual cortex.

All reasonable doubt that the senses can be rewired was recently put to rest in one of the most amazing plasticity experiments of our time. It involved rewiring not touch and vision pathways, as Bach-y-Rita had done, but those for hearing and vision—literally. Mriganka Sur, a neuroscientist, surgically rewired the brain of a very young ferret. Normally the optic nerves run from the eyes to the visual cortex, but Sur surgically redirected the optic nerves from the ferret's visual to its auditory (hearing) cortex and discovered that the ferret learned to see. Using electrodes inserted into the ferret's brain, Sur proved that when the ferret was seeing, the neurons in its auditory cortex were firing and doing the visual processing. The auditory cortex, as plastic as Bach-y-Rita had always imagined, had reorganized itself, so that it had the structure of the visual cortex. Though the ferrets that had this surgery did not have 20/20 vision, they had about a third of that, or 20/60—no worse than some people who wear eyeglasses.

Till recently, such transformations would have seemed utterly inexplicable. But Bach-y-Rita, by showing that our brains are more flexible than localizationism admits, has helped to invent a more accurate view of the brain that allows for such changes. Before he did this work, it was acceptable to say, as most neuroscientists do, that we have a "visual cortex" in our occipital lobe that processes vision, and an "auditory cortex" in our temporal lobe that processes hearing. From Bach-y-Rita we have learned that the matter is more complicated and that these areas of the brain are plastic processors, connected to each other and capable of processing an unexpected variety of input.

Cheryl has not been the only one to benefit from Bach-y-Rita's strange hat. The team has since used the device to train fifty more patients to improve their balance and walking. Some had the same damage Cheryl had; others have had brain trauma, stroke, or Parkinson's disease.

Paul Bach-y-Rita's importance lies in his being the first of his generation of neuroscientists both to understand that the brain is plastic and to apply this knowledge in a practical way to ease human suffering. Implicit in all his work is the idea that we are all born with a far more adaptable, all-purpose, opportunistic brain than we have understood.

When Cheryl's brain developed a renewed vestibular sense—or blind subjects' brains developed new paths as they learned to recognize objects, perspective, or movement—these changes were not the mysterious exception to the rule but the rule: the sensory cortex is plastic and adaptable. When Cheryl's brain learned to respond to the artificial receptor that replaced her damaged one, it was not doing anything out of the ordinary. Recently Bach-y-Rita's work has inspired cognitive scientist Andy Clark to wittily argue that we are "natural-born cyborgs," meaning that brain plasticity allows us to attach ourselves to machines, such as computers and electronic tools, quite naturally. But our brains also restructure themselves in response to input from the simplest tools too, such as a blind man's cane. Plasticity has been, after all, a property inherent in the brain since prehistoric times. The brain is a far more open system than we ever imagined, and nature has gone very far to help us perceive and take in the world around us. It has given us a brain that survives in a changing world by changing itself.