The Brain That Changes Itself

Stories of Personal Triumph from the Frontiers of Brain Science

NORMAN DOIDGE, M.D.

For Eugene L. Goldberg, M.D., because you said you might like to read it

Contents

Note to the Reader

xi

Preface

xiii

1

A Woman Perpetually Falling . . .

Rescued by the Man Who Discovered
the Plasticity of Our Senses

1

2 Building Herself a Better Brain

A Woman Labeled "Retarded" Discovers How to Heal Herself

27
3 Redesigning the Brain
A Scientist Changes Brains to Sharpen Perception and Memory, Increase Speed of Thought, and Heal Learning Problems
45

4 Acquiring Tastes and Loves
What Neuroplasticity Teaches Us About Sexual Attraction and Love
93

5 Midnight Resurrections
Stroke Victims Learn to Move and Speak Again
132

6 Brain Lock Unlocked
Using Plasticity to Stop Worries, OPsessions, Compulsions, and Bad Habits
164

7 Pain
The Dark Side of Plasticity
177

8 Imagination
How Thinking Makes It So
196

9 Turning Our Ghosts into Ancestors
Psychoanalysis as a Neuroplastic Therapy
215

10
Rejuvenation
The Discovery of the Neuronal Stem Cell and Lessons for Preserving Our Brains
245

11
More than the Sum of Her Parts
A Woman Shows Us How Radically Plastic the Brain Can Be
258

Appendix 1
The Culturally Modified Brain
287

Appendix 2
Plasticity and the Idea of Progress
313

Note to the Reader
All the names of people who have undergone neuroplastic transformations are real, except in the few places indicated, and in the cases of children and their families.

The Notes and References section at the end of the book includes comments on both the chapters and the appendices.
Preface

This book is about the revolutionary discovery that the human brain can change itself, as told through the stories of the scientists, doctors, and patients who have together brought about these astonishing transformations. Without operations or medications, they have made use of the brain's hitherto unknown ability to change. Some were patients who had what were thought to be incurable brain problems; others were people without specific problems who simply wanted to improve the functioning of their brains or preserve them as they aged. For four hundred years this venture would have been inconceivable because mainstream medicine and science believed that brain anatomy was fixed. The common wisdom was that after childhood the brain changed only when it began the long process of decline; that when brain cells failed to develop properly, or were injured, or died, they could not be replaced. Nor could the brain ever alter its structure and find a new way to function if part of it was damaged. The theory of the unchanging brain decreed that people who were born with brain or mental limitations, or who sustained brain damage, would be limited or damaged for life. Scientists who wondered if the healthy brain might be improved or preserved through activity or mental exercise were told not to waste their time, A neurological nihilism—a sense that treatment for many brain problems was ineffective or even unwarranted—had taken hold, and it spread through our culture, even stunting our overall view of human nature. Since the brain could not change, human nature, which emerges from it, seemed necessarily fixed and unalterable as well.

The belief that the brain could not change had three major sources: the fact that brain-damaged patients could so rarely make full recoveries; our inability to observe the living brain's microscopic activities; and the idea—dating back to the beginnings of modern science—that the brain is like a glorious machine. And while machines do many extraordinary things, they don't change and grow.

I became interested in the idea of a changing brain because of my work as a research psychiatrist and psychoanalyst. When patients did not progress psychologically as much as hoped, often the conventional medical wisdom was that their problems were deeply "hardwired" into an unchangeable brain. "Hardwiring" was another machine metaphor
coming from the idea of the brain as computer hardware, with permanently connected circuits, each designed to perform a specific, unchangeable function.

When I first heard news that the human brain might not be hardwired, I had to investigate and weigh the evidence for myself. These investigations took me far from my consulting room.

I began a series of travels, and in the process I met a band of brilliant scientists, at the frontiers of brain science, who had, in the late 1960s or early 1970s, made a series of unexpected discoveries. They showed that the brain changed its very structure with each different activity it performed, perfecting its circuits so it was better suited to the task at hand. If certain "parts" failed, then other parts could sometimes take over. The machine metaphor, of the brain as an organ with specialized parts, could not fully account for changes the scientists were seeing. They began to call this fundamental brain property "neuroplasticity."

Neuro is for "neuron," the nerve cells in our brains and nervous systems. Plastic is for "changeable, malleable, modifiable." At first many of the scientists didn't dare use the word "neuroplasticity" in their publications, and their peers belittled them for promoting a fanciful notion. Yet they persisted, slowly overturning the doctrine of the unchanging brain. They showed that children are not always stuck with the mental abilities they are born with; that the damaged brain can often reorganize itself so that when one part fails, another can often substitute; that if brain cells die, they can at times be replaced; that many "circuits" and even basic reflexes that we think are hardwired are not. One of these scientists even showed that thinking, learning, and acting can turn our genes on or off, thus shaping our brain anatomy and our behavior—surely one of the most extraordinary discoveries of the twentieth century.

In the course of my travels I met a scientist who enabled people who had been blind since birth to begin to see, another who enabled the deaf to hear; I spoke with people who had had strokes decades before and had been declared incurable, who were helped to recover with neuroplastic treatments; I met people whose learning disorders were cured and whose IQs were raised; I saw evidence that it is possible for eighty-year-olds to sharpen their memories to function the way they did when they were fifty-five. I saw people rewire their brains with their thoughts, to cure previously incurable obsessions and traumas. I spoke with Nobel laureates who were hotly debating how we must rethink our model of the brain now that we know it is ever changing.
The idea that the brain can change its own structure and function through thought and activity is, I believe, the most important alteration in our view of the brain since we first sketched out its basic anatomy and the workings of its basic component, the neuron. Like all revolutions, this one will have profound effects, and this book, I hope, will begin to show some of them. The neuroplastic revolution has implications for, among other things, our understanding of how love, sex, grief, relationships, learning, addictions, culture, technology, and psychotherapies change our brains. All of the humanities, social sciences, and physical sciences, insofar as they deal with human nature, are affected, as are all forms of training. All of these disciplines will have to come to terms with the fact of the self-changing brain and with the realization that the architecture of the brain differs from one person to the next and that it changes in the course of our individual lives.

While the human brain has apparently underestimated itself, neuroplasticity isn’t all good news; it renders our brains not only more resourceful but also more vulnerable to outside influences. Neuroplasticity has the power to produce more flexible but also more rigid behaviors—a phenomenon I call "the plastic paradox." Ironically, some of our most stubborn habits and disorders are products of our plasticity. Once a particular plastic change occurs in the brain and becomes well established, it can prevent other changes from occurring. It is by understanding both the positive and negative effects of plasticity that we can truly understand the extent of human possibilities.

Because a new word is useful for those who do a new thing, I call the practitioners of this new science of changing brains "neuroplasticians."

What follows is the story of my encounters with them and the patients they have transformed.

---

**The Brain That Changes Itself**

---

1

**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 genta-micin," 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
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 neuro-science 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 Rene 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 muscle), visuall 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

...rthest 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 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 Bogota, 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,
foxcusing 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.

2

Building Herself a Better Brain

A Woman Labeled "Retarded" Discovers How to Heal Herself

The scientists who make important discoveries about the brain are often those whose own brains are extraordinary, working on those whose brains are damaged. It is rare that the person who makes an important discovery is the one with the defect, but there are some exceptions. Barbara Arrowsmith Young is one of these.

"Asymmetry" is the word that best describes her mind when she was a schoolgirl. Born in Toronto in 1951 and raised in Peterborough, Ontario, Barbara had areas of brilliance as a child—her auditory and visual memory both tested in the ninety-ninth percentile. Her frontal lobes were remarkably developed, giving her a driven, dogged quality. But her brain was "asymmetrical," meaning that these exceptional abilities coexisted with areas of retardation.

This asymmetry left its chaotic handwriting on her body as well. Her mother made a joke of it. "The obstetrician must have yanked you out by your right leg," which was longer than her left, causing her pelvis to shift. Her right arm never straightened, her right side was larger than her left, her left eye less alert, Her spine was asymmetrical and twisted with scoliosis.

She had a confusing assortment of serious learning disabilities.
The area of her brain devoted to speech, Broca's area, was not working properly, so she had trouble pronouncing words. She also lacked the capacity for spatial reasoning. When we wish to move our bodies in space, we use spatial reasoning to construct an imaginary pathway in our heads before executing our movements. Spatial reasoning is important for a baby crawling, a dentist drilling a tooth, a hockey player planning his moves. One day when Barbara was three she decided to play matador and bull. She was the bull, and the car in the driveway was the matador's cape. She charged, thinking she would swerve and avoid it, but she misjudged the space and ran into the car, ripping her head open. Her mother declared she would be surprised if Barbara lived another year.

Spatial reasoning is also necessary for forming a mental map of where things are. We use this kind of reasoning to organize our desks or remember where we have left our keys. Barbara lost everything all the time. With no mental map of things in space, out of sight was literally out of mind, so she became a "pile person" and had to keep everything she was playing with or working on in front of her in piles, and her closets and dressers open. Outdoors she was always getting lost.

She also had a "kinesthetic" problem. Kinesthetic perception allows us to be aware of where our body or limbs are in space, enabling us to control and coordinate our movements. It also helps us recognize objects by touch. But Barbara could never tell how far her arms or legs had moved on her left side. Though a tomboy in spirit, she was clumsy. She couldn't hold a cup of juice in her left hand without spilling it. She frequently tripped or stumbled. Stairs were treacherous. She also had a decreased sense of touch on her left and was always bruising herself on that side. When she eventually learned to drive, she kept denting the left side of the car.

She had a visual disability as well. Her span of vision was so narrow that when she looked at a page of writing, she could take in only a few letters at a time.

But these were not her most debilitating problems. Because the part of her brain that helps to understand the relationships between symbols wasn't functioning normally, she had trouble understanding grammar, math concepts, logic, and cause and effect. She couldn't distinguish between "the father's brother" and "the brother's father." The double negative was impossible for her to decipher. She couldn't read a clock because she couldn't understand the relationship between the hands. She literally couldn't tell her left hand from her right, not only because she lacked a spatial map but because she couldn't understand the relationship between "left" and "right." Only with extraordinary mental effort and constant repetition could she learn to relate symbols to one another.
She reversed b, d, q, and p, read "was" as "saw," and read and wrote from right to left, a disability called mirror writing. She was right-handed, but because she wrote from right to left, she smeared all her work. Her teachers thought she was being obstreperous. Because she was dyslexic, she made reading errors that cost her dearly. Her brothers kept sulfuric acid for experiments in her old nose-drops bottle.

Once when she decided to treat herself for sniffles, Barbara misread the new label they had written. Lying in bed with acid running into her sinuses, she was too ashamed to tell her mother of yet another mishap.

Unable to understand cause and effect, she did odd things socially because she couldn't connect behavior with its consequences. In kindergarten she couldn't understand why, if her brothers were in the same school, she couldn't leave her class and visit them in theirs whenever she wanted. She could memorize math procedures but couldn't understand math concepts. She could recall that five times five equals twenty-five but couldn't understand why. Her teachers responded by giving her extra drills, and her father spent hours tutoring her, to no avail. Her mother held up flash cards with simple math problems on them. Because Barbara couldn't figure them out, she found a place to sit where the sun made the paper translucent, so she could read the answers on the back. But the attempts at remediation didn't get at the root of the problem; they just made it more agonizing.

Wanting desperately to do well, she got through elementary school by memorizing during lunch hours and after school. In high school her performance was extremely erratic. She learned to use her memory to cover her deficits and with practice could remember pages of facts. Before tests she prayed they would be fact-based, knowing she could score 100; if they were based on understanding relationships, she would probably score in the low teens.

**Barbara understood nothing in real time, only after the fact,**

in lag time. Because she did not understand what was happening around her while it was occurring, she spent hours reviewing the past, to make its confusing fragments come together and become comprehensible. She had to replay simple conversations, movie dialogue, and song lyrics twenty times over in her head because by the time she got to the end of a sentence, she could not recall what the beginning meant.
Her emotional development suffered. Because she had trouble with logic, she could not pick up inconsistencies when listening to smooth talkers and so she was never sure whom to trust. Friendships were difficult, and she could not have more than one relationship at a time.

But what plagued her most was the chronic doubt and uncertainty that she felt about everything. She sensed meaning everywhere but could never verify it. Her motto was "I don't get it." She told herself, "I live in a fog, and the world is no more solid than cotton candy." Like many children with serious learning disabilities, she began to think she might be crazy.

Barbara grew up in a time when little help was available.

"In the 1950s, in a small town like Peterborough, you didn't talk about these things," she says. "The attitude was, you either make it or you don't. There were no special-ed teachers, no visits to medical specialists or psychologists. The term 'learning disabilities' wouldn't be widely used for another two decades. My grade-one teacher told my parents I had 'a mental block' and I wouldn't ever learn the way others did. That was as specific as it got. You were either bright, average, slow, or mentally retarded."

If you were mentally retarded, you were placed in "opportunity classes." But that was not the place for a girl with a brilliant memory who could ace vocabulary tests. Barbara's childhood friend Donald Frost, now a sculptor, says, "She was under incredible academic pressure. The whole Young family were high achievers. Her father, Jack, was an electrical engineer and inventor with thirty-four patents for Canadian General Electric. If you could pull Jack from a book for dinner, it was a miracle. Her mother, Mary, had the attitude: 'You will succeed; there is no doubt,' and 'If you have a problem, fix it.' Barbara was always incredibly sensitive, warm, and caring," Frost continues, "but she hid her problems well. It was hush-hush. In the postwar years there was a sense of integrity that meant you didn't draw attention to your disabilities any more than you would to your pimples."

Barbara gravitated toward the study of child development, somehow to sort things out for herself. As an undergraduate at the University of Guelph, her great mental disparities were again apparent. But fortunately her teachers saw that she had a remarkable ability to pick up nonverbal cues in the child-observation laboratory,

and she was asked to teach the course. She felt there must have been some mistake. Then she was accepted into graduate school at the Ontario Institute for Studies in Education (OISE). Most students read a research paper once or twice, but typically Barbara had to read one twenty times as well as many of its sources to get even a
fleeting sense of its meaning. She survived on four hours of sleep a night.

Because Barbara was brilliant in so many ways, and so adept at child observation, her teachers in graduate school had trouble believing she was disabled. It was Joshua Cohen, another gifted but learning-disabled student at OISE, who first understood. He ran a small clinic for learning-disabled kids that used the standard treatment, "compensations," based on the accepted theory of the time;

once brain cells die or fail to develop, they cannot be restored. Compensations work around the problem. People with trouble reading listen to audiotapes. Those who are "slow" are given more time on tests. Those who have trouble following an argument are told to color-code the main points. Joshua designed a compensation program for Barbara, but she found it too time-consuming. Moreover, her thesis, a study of learning-disabled children treated with compensations at the OISE clinic, showed that most of them were not really improving. And she herself had so many deficits that it was sometimes hard to find healthy functions that could work around her deficits. Because she had had such success developing her memory, she told Joshua she thought there must be a better way.

One day Joshua suggested she look into some books by Aleksandr Luria that he’d been reading. She tackled them, going over the difficult passages countless times, especially a section in Luria's *Basic Problems of Neurolinguistics* about people with strokes or wounds who had trouble with grammar, logic, and reading clocks. Luria, born in 1902, came of age in revolutionary Russia. He was deeply interested in psychoanalysis, corresponded with Freud, and wrote papers on the psychoanalytic technique of "free association," in which patients say everything that comes to mind. His goal was to develop objective methods to assess Freudian ideas. While still in his twenties, he invented the prototype of the lie detector. When the Great Purges of the Stalin era began, psychoanalysis became *scientia non grata*, and Luria was denounced. He delivered a public recantation, admitting to having made certain "ideological mistakes." Then, to remove himself from view, he went to medical school.

But he had not totally finished with psychoanalysis. Without calling attention to his work, he integrated aspects of the psycho-analytic method and of psychology into neurology, becoming the founder of neuropsychology. His case histories, instead of being brief vignettes focused on symptoms, described his patients at length. As Oliver Sacks wrote, "Luria's case histories, indeed, can only be compared to Freud's in their precision, their vitality, their wealth and depth of detail." One of Luria's books, *The Man with a Shattered World*, was the summary of, and commentary on, the diary of a patient with a very peculiar condition.

At the end of May 1943 Comrade Lyova Zazetsky, a man who seemed like a boy, came to Luria's office in the rehabilitation hospital where he was working. Zazetsky was a young Russian lieutenant who had just been injured in the battle of Smolensk, where poorly equipped Russians
had been thrown against the invading Nazi war machine. He had sustained a bullet wound to the
head, with massive damage on the left side, deep inside his brain. For a long time he lay in a
coma. When Zazetsky awoke, his symptoms were very odd. The

shrapnel had lodged in the part of the brain that helped him understand relationships between
symbols. He could no longer understand logic, cause and effect, or spatial relationships. He
couldn't distinguish his left from his right. He couldn't understand the elements of
grammar dealing with relationships. Prepositions such as "in," "out,"
"before," "after," "with," and 'without" had become meaningless to him. He couldn't
comprehend a whole word, understand a whole sentence, or recall a complete memory because
doing any of those things would require relating symbols. He could grasp only fleeting
fragments. Yet his frontal lobes—which allowed him to seek out what is relevant and to plan,
strategize, form intentions, and pursue
them—were spared, so he had the capacity to recognize his defects,

and the wish to overcome them. Though he could not read, which is largely a perceptual
activity, he could write, because it is an intentional one. He began a fragmentary diary he
called I'll Fight On that swelled to three thousand pages. "I was killed March 2,1943," he
wrote, "but because of some vital power of my organism, I miraculously remained alive."

Over thirty years Luria observed him and reflected on the way
Zazetsky's wound affected his mental activities. He would witness
Zazetsky's relentless fight "to live, not merely exist."

Reading Zazetsky's diary, Barbara thought "He is describing my life."

"I knew what the word? 'mother' and 'daughter' meant but not the expression 'mother's
daughter,'" Zazetsky wrote. "'The expressions 'mother's daughter' and 'daughter's mother'
sounded just the same to me. I also had trouble with expressions like 'Is an elephant
bigger than a fly?' All I could figure out was that a fly was small and an elephant is big,
but I didn't understand the words 'bigger' and 'smaller.'"

While watching a film, Zazetsky wrote, "before I've had a chance to figure out what the
actors are saying, a new scene begins."

Luria began to make sense of the problem. Zazetsky's bullet had lodged in the left
hemisphere, at the junction of three major perceptual areas where the temporal lobe
(which normally processes sound and language), the occipital lobe (which normally
processes visual images), and the parietal lobe (which normally processes spatial relationships and integrates information from different senses) meet. At this junction perceptual input from those three areas is brought together and associated. While Zazetsky could perceive properly, Luria realized he could not relate his different perceptions, or parts of things to wholes. Most important, he had great difficulty relating a number of symbols to one another, as we normally do when we think with words. Thus Zazetsky often spoke in malapropisms. It was as though he didn't have a large enough net to catch and hold words and their meanings, and he often could not relate words to their meanings or definitions. He lived with fragments and wrote, 'I'm in a fog all the time ... All that flashes through my mind are images . . hazy visions that suddenly appear and just as suddenly disappear ... I simply can't understand or remember what these mean.'

For the first time, Barbara understood that her main brain deficit had an address. But Luria did not provide the one thing she needed: a treatment. When she realized how impaired she really was, she found herself more exhausted and depressed and thought she could not go on this way. On subway platforms she looked for a spot from which to jump for maximum impact.

It was at this point in her life, while she was twenty-eight and still in graduate school, that a paper came across her desk. Mark Rosen-eig of the University of California at Berkeley had studied rats in stimulating and nonstimulating environments, and in postmortem exams he found that the brains of the stimulated rats had more neurotransmitters, were heavier, and had better blood supply than those from the less stimulating environments. He was one of the first scientists to demonstrate neuroplasticity by showing that activity could produce changes in the structure of the brain.

For Barbara, lightning struck. Rosenzweig had shown that the brain could be modified. Though many doubted it, to her this meant that compensation might not be the only answer. Her own breakthrough would be to link Rosenzweig's and Luria's research.

She isolated herself and began toiling to the point of exhaustion, week after week—with only brief breaks for sleep—at mental exercises she designed, though she had no guarantee they would lead anywhere. Instead of practicing compensation, she exercised her most weakened function—relating a number of symbols to each other. One exercise involved reading hundreds of cards picturing clock faces showing different times. She had Joshua Cohen write the
correct time on the backs. She shuffled the cards so she couldn't memorize the answers. She turned up a card, attempted to tell the time, checked the answer, then moved on to the next card as fast as she could. When she couldn't get the time right, she'd spend hours with a real clock, turning the hands slowly, trying to understand why, at 2:45, the hour hand was three-quarters of the way toward the three.

When she finally started to get the answers, she added hands for seconds and sixtieths of a second. At the end of many exhausting weeks, not only could she read clocks faster than normal people, but she noticed improvements in her other difficulties relating to symbols and began for the first time to grasp grammar, math, and logic. Most important, she could understand what people were saying as they said it. For the first time in her life, she began to live in real time. Spurred on by her initial success, she designed exercises for her other disabilities—her difficulties with space, her trouble with knowing where her limbs were, and her visual disabilities—and brought them up to average level.

Barbara and Joshua Cohen married, and in 1980 they opened the Arrowsmith School in Toronto. They did research together, and Barbara continued to develop brain exercises and to run the school from day to day. Eventually they parted, and Joshua died in 2000.

Because so few others knew about or accepted neuroplasticity or believed that the brain might be exercised as though it were a muscle, there was seldom any context in which to understand her work. She was viewed by some critics as making claims—that learning disabilities were treatable—that couldn't be substantiated. But far from being plagued by uncertainty, she continued to design exercises for the brain areas and functions most commonly weakened in those with learning disabilities. In these years before high-tech brain scans were available, she relied on Luria's work to understand which areas

or the brain commonly processed which mental functions. Luria had formed his own map of the brain by working with patients like Zazetsky. He observed where a soldier's wound had occurred and related this location to the mental functions lost. Barbara found that learning disorders were often milder versions of the thinking deficits seen in Luria's patients.

Applicants to the Arrowsmith School—children and adults alike—undergo up to forty hours of assessments, designed to determine precisely which brain functions are weak and whether they might be helped. Accepted students, many of whom were distracted in regular schools, sit quietly working at their computers. Some, diagnosed with attention-deficit as well as learning disorders, were on Ritalin when they entered the school. As their exercises progress, some can come off medication, because their attention problems are secondary to their underlying learning disorders.

At the school, children who, like Barbara, had been unable to read a clock now work at computer exercises reading mind-numbingly complex ten-handed clocks (with hands not only for minutes,
hours, and seconds but also for other time divisions, such as days, months, years) in mere seconds. They sit quietly, with intense concentration,

until they get enough answers right to progress to the nest level, when they shriek out a loud "Yes!" and their computer screen lights up to congratulate them. By the time they finish, they can read clocks far more complex than those any "normal" person can read.

At other tables children are studying Urdu and Persian letters to strengthen their visual memories. The shapes of these letters are unfamiliar, and the brain exercise requires the students to learn to recognize these alien shapes quickly.

Other children, like little pirates, wear eye patches on their left eyes and diligently trace intricate lines, squiggles, and Chinese letters with pens. The eye patch forces visual input into the right eye, then to the side of the brain where they have a problem. These children are not simply learning to write better. Most of them come with three related problems: trouble speaking in a smooth, flowing way, writing neatly, and reading. Barbara, following Luria, believes that all three difficulties are caused by a weakness in the brain function that normally helps us to coordinate and string together a number of movements when we perform these tasks.

When we speak, our brain converts a sequence of symbols—the letters and words of the thought—into a sequence of movements made by our tongue and lip muscles. Barbara believes, again following Luria, that the part of the brain that strings these movements together is the left premotor cortex of the brain. I referred several people with a weakness in this brain function to the school. One boy with this problem was always frustrated, because his thoughts came faster than he could turn them into speech, and he would often leave out chunks of information, have trouble finding words, and ramble. He was a very social person yet could not express himself and so remained silent much of the time. When he was asked a question in class, he often knew the answer but took such a painfully long time to get it out that he appeared much less intelligent than he was, and he began to doubt himself.

When we write a thought, our brain converts the words—which are symbols—into movements of the fingers and hands. The same boy had very jerky writing because his processing capacity for converting symbols into movements was easily overloaded, so he had to write with many separate, small movements instead of long, flowing ones. Even though he had been taught cursive writing, he preferred to print. (As adults, people with this problem can often be identified because they prefer to print or type. When we print, we make each letter separately, with just a few pen movements, which is less demanding on the brain. In cursive we write several letters at a time, and the brain must process more complex movements.) Writing was especially painful for the boy, since he often knew the right answers on tests but wrote so slowly that he couldn't get them all down. Or he would think of one word, letter, or number but write another. These
children are often accused of being careless, but actually their over-loaded brains fire the wrong motor movements.

Students with this disability also have reading problems. Normally when we read, the brain reads part of a sentence, then directs the eyes to move the right distance across the page to take in the next part of the sentence, requiring an ongoing sequence of precise eye movements.

The boy's reading was very slow because he skipped words, lost his place, and then lost his concentration. Reading was overwhelming and exhausting. On exams he would often misread the question, and when he tried to proofread his answers, he'd skip whole sections.

At the Arrowsmith School this boy's brain exercises involved tracing complex lines to stimulate his neurons in the weakened pre-motor area. Barbara has found that tracing exercises improve children in all three areas—speaking, writing, and reading. By the time the boy graduated, he read above grade level and could read for pleasure for the first time. He spoke more spontaneously in longer, fuller sentences, and his writing improved.

At the school some students listen to CDs and memorize poems to improve their weak auditory memories. Such children often forget instructions and are thought to be irresponsible or lazy, when in fact they have a brain difficulty. Whereas the average person can remember seven unrelated items (such as a seven-digit phone number), these people can remember only two or three. Some take notes compulsively, so they won't forget. In severe cases, they can't follow a song lyric from beginning to end, and they get so overloaded they just tune out. Some have difficulty remembering not only spoken language but even their own thoughts, because thinking with language is slow. This deficit can be treated with exercises in rote memorizing.

Barbara has also developed brain exercises for children who are socially clumsy because they have a weakness in the brain function that would allow them to read nonverbal cues. Other exercises are for those who have frontal lobe deficits and who are impulsive or have problems planning, developing strategies, sorting out what is relevant, forming goals, and sticking to them. They often appear disorganized, flighty, and unable to learn from their mistakes. Barbara believes that many people labeled "hysterical" or "antisocial" have weaknesses in this area.

The brain exercises are life-transforming. One American graduate told me that when he came to the school at thirteen, his math and
reading skills were still at a third-grade level. He had been told after
neuropsychological testing at Tufts University that he would never improve. His mother
had tried him in ten different schools for students with learning disabilities, but none had
helped. After three years at Arrowsmith, he was reading and doing math at a tenth-grade
level. Now he has graduated from college and works in venture capital. Another student
came to Arrowsmith at sixteen reading at a first-grade level. His parents, both teachers,
had tried all the standard compensation techniques. After fourteen months at Arrowsmith
he is reading at a seventh-grade level.

We all have some weak brain functions, and such neuroplasticity-based techniques have
great potential to help almost everyone. Our weak spots can have a profound effect on
our professional success, since most careers require the use of multiple brain functions.
Barbara used brain exercises to rescue a talented artist who had a first-rate drawing
ability and sense of color but a weak ability to recognize the shape of objects. (The ability
to recognize shapes depends on a brain function quite different from those functions
required for drawing or seeing color; it is the same skill that allows some people to excel
at games like Where's Waldo? Women are often better at it at than men, which is why
men seem to have more difficulty finding things in the refrigerator.)

Barbara also helped a lawyer, a promising litigator who, because of a Broca's area
pronunciation deficit, spoke poorly in court. Since

expending the extra mental effort to support a weak area seems to divert resources from
strong areas, a person with a Broca's problem may also find it harder to think while
talking. After practicing brain exercises focused on Broca's area, the lawyer went on to a
successful courtroom career.

The Arrowsmith approach, and the use of brain exercises generally, has major
implications for education. Clearly many children would benefit from a brain-area-based
assessment to identify their weakened functions and a program to strengthen them—a far
more productive approach than tutoring that simply repeats a lesson and leads to endless
frustration. When "weak links in the chain" are strengthened, people gain access to skills
whose development was formerly blocked, and they feel enormously liberated. A patient
of mine, before he did the brain exercises, had a sense that he was very bright but could
not make full use of his intelligence. For a long time I mistakenly thought his problems
were based primarily on psychological conflicts, such as a fear of competition, and buried
conflicts about surpassing his parents and siblings. Such conflicts did exist and did hold
him back. But I came to see that his conflict about learning—his wish to avoid it—was
based mostly on years of frustration and on a very legitimate fear of failure based on his
brain's limits. Once he was liberated from his difficulties by Arrowsmith's exercises, his
innate love of learning emerged full force.
The irony of this new discovery is that for hundreds of years educators did seem to sense that children’s brains had to be built up through exercises of increasing difficulty that strengthened brain functions. Up through the nineteenth and early twentieth centuries a classical education often included rote memorization of long poems in foreign languages, which strengthened the auditory memory (hence thinking in language) and an almost fanatical attention to handwriting, which probably helped strengthen motor capacities and thus not only helped handwriting but added speed and fluency to reading and speaking. Often a great deal of attention was paid to exact elocution and to perfecting the pronunciation of words. Then in the 1960s educators dropped such traditional exercises from the curriculum, because they were too rigid, boring, and "not relevant." But the loss of these drills has been costly; they may have been the only opportunity that many students had to systematically exercise the brain function that gives us fluency and grace with symbols. For the rest of us, their disappearance may have contributed to the general decline of eloquence, which requires memory and a level of auditory brainpower unfamiliar to us now. In the Lincoln-Douglas debates of 1858 the debaters would comfortably speak for an hour or more without notes, in extended memorized paragraphs; today many of the most learned among us, raised in our most elite schools since the 1960s, prefer the omnipresent PowerPoint presentation—the ultimate compensation for a weak premotor cortex.

Barbara Arrowsmith Young’s work compels us to imagine how much good might be accomplished if every child had a brain-based assessment and, if problems were found, a tailor-made program created to strengthen essential areas in the early years, when neuroplasticity is greatest. It is far better to nip brain problems in the bud than to allow the child to wire into his brain the idea that he is "stupid," begin to hate school and learning, and stop work in the weakened area, losing whatever strength he may have. Younger children often progress more quickly through brain exercises than do adolescents, perhaps because in an immature brain the number of connections among neurons, or synapses, is 50 percent greater than in the adult brain. When we reach adolescence, a massive “pruning back” operation begins in the brain, and synaptic connections and neurons that have not been used extensively suddenly die off—a classic case of "use it or lose it." It is probably best to strengthen weakened areas while all this extra cortical real estate is available. Still, brain-based assessments can be helpful all through school and even in college and university, when many students who did well in high school fail
because their weak brain functions are overloaded by the increased demand. Even apart from these crises, every adult could benefit from a brain-based cognitive assessment, a cognitive fitness test, to help them better understand their own brain.

It's been years since Mark Rosenzweig first did the rat experiments that inspired Barbara and showed her that enriched environments and stimulation lead the brain to grow. Over the years his labs and others have shown that stimulating the brain makes it grow in almost every conceivable way. Animals raised in enriched environments—surrounded by other animals, objects to explore, toys to roll, ladders to climb, and running wheels—learn better than genetically identical animals that have been reared in impoverished environments. Acetylcholine, a brain chemical essential for learning, is higher in rats trained on difficult spatial problems than in rats trained on simpler problems. Mental training or life in enriched environments increases brain weight by 5 percent in the cerebral cortex of animals and up to 9 percent in areas that the training directly stimulates. Trained or stimulated neurons develop 25 percent more branches and increase their size, the number of connections per neuron, and their blood supply. These changes can occur late in life, though they do not develop as rapidly in older animals as in younger ones. Similar effects of training and enrichment on brain anatomy have been seen in all types of animals tested to date.

For people, postmortem examinations have shown that education increases the number of branches among neurons. An increased number of branches drives the neurons farther apart, leading to an increase in the volume and thickness of the brain. The idea that the brain is like a muscle that grows with exercise is not just a metaphor.

Some things can never be put together again. Lyova Zazetsky's diaries remained mostly a series of fragmented thoughts till the end. Aleksandr Luria, who figured out the meaning of those fragments,

could not really help him. But Zazetsky's life story made it possible for Barbara Arrowsmith Young to heal herself and now others.

Today Barbara Arrowsmith Young is sharp and funny, with no noticeable bottlenecks in her mental processes. She flows from one activity to the next, from one child to the next, a master of many skills.

She has shown that children with learning disabilities can often go beyond compensations and correct their underlying problem.

Like all brain exercise programs, hers work best and most quickly for
people with only a few areas of difficulty. But because she has developed exercises for so many brain dysfunctions, she is often able to help children with multiple learning disabilities—children like herself, before she built herself a better brain.

3

Redesigning the Brain

A Scientist Changes Brains to Sharpen Perception and Memory, Increase Speed of Thought, and Heal Learning Problems

Michael Merzenich is a driving force behind scores of neuro-plastic innovations and practical inventions, and I am on the road to Santa Rosa, California, to find him. His is the name most frequently praised by other neuroplasticians, and he's by far the hardest to track down. Only when I found out that he would be at a conference in Texas, went there, and sat myself down beside him, was I finally able to set up a meeting in San Francisco. "Use this e-mail address," he says. "And if you don't respond again?" "Be persistent."

At the last minute, he switches our meeting to his villa in Santa Rosa.

Merzenich is worth the search.

The Irish neuroscientist Ian Robertson has described him as "the world's leading researcher on brain plasticity." Merzenich's specialty is improving people's ability to think and perceive by redesigning the brain by training specific processing areas, called brain maps, so that they do more mental work. He has also, perhaps more than any other scientist, shown in rich scientific detail how our brain-processing areas change.

This villa in the Santa Rosa hills is where Merzenich slows down
and regenerates himself. This air, these trees, these vineyards, seem like a piece of Tuscany transplanted into North America. I spend the night here with him and his family, and then in the morning we are off to his lab in San Francisco.

Those who work with him call him "Merz," to rhyme with "whirs" and "stirs." As he drives his small convertible to meetings— he's been double-booked much of the afternoon—his gray hair flies in the wind, and he tells me that many of his most vivid memories, in this, the second half of his life—he's sixty-one—are of conversations about scientific ideas. I hear him pour them into his cell phone, in his crackling voice. As we pass over one of San Francisco's glorious bridges, he pays a toll he doesn't have to because he's so involved with the concepts we are discussing. He has dozens of collaborations and experiments all going on at once and has started several companies. He describes himself as "just this side of crazy." He is not, but he is an interesting mix of intensity and informality. He was born in Lebanon, Oregon, of German stock, and though his name is Teutonic and his work ethic unrelenting, his speech is West Coast, easygoing, down-to-earth.

Of neuroplasticians with solid hard-science credentials, it is Merzenich who has made the most ambitious claims for the field: that brain exercises may be as useful as drugs to treat diseases as severe as schizophrenia; that plasticity exists from the cradle to the grave; and that radical improvements in cognitive functioning— how we learn, think, perceive, and remember—are possible even in the elderly. His latest patents are for techniques that show promise in allowing adults to learn language skills, without effortful memorization. Merzenich argues that practicing a new skill, under the right conditions, can change hundreds of millions and possibly billions of the connections between the nerve cells in our brain maps.

If you are skeptical of such spectacular claims, keep in mind that they come from a man who has already helped cure some disorders that were once thought intractable. Early in his career Merzenich developed, along with his group, the most commonly used design for the cochlear implant, which allows congenitally deaf children to hear. His current plasticity work helps learning-disabled students improve their cognition and perception. These techniques—his series of plasticity-based computer programs, Fast ForWord—have already helped hundreds of thousands. Fast ForWord is disguised as a children's game. What is amazing about it is how quickly the change occurs. In some cases people who have had a lifetime of cognitive difficulties get better after only thirty to sixty hours of treatment. Unexpectedly, the program has also helped a number of autistic children.

Merzenich claims that when learning occurs in a way consistent with the laws that govern brain plasticity, the mental "machinery" of the brain can be improved so that we learn and perceive with greater
precision, speed, and retention.

Clearly when we learn, we increase what we know. But Merzenich's claim is that we can also change the very structure of the brain itself and increase its capacity to learn. Unlike a computer, the brain is constantly adapting itself.

"The cerebral cortex," he says of the thin outer layer of the brain, "is actually selectively refining its processing capacities to fit each task at hand." It doesn't simply learn; it is always "learning how to learn." The brain Merzenich describes is not an inanimate vessel that we fill; rather it is more like a living creature with an appetite, one that can grow and change itself with proper nourishment and exercise. Before Merzenich's work, the brain was seen as a complex machine, having unalterable limits on memory, processing speed, and intelligence. Merzenich has shown that each of these assumptions is wrong. Merzenich did not set out to understand how the brain changes.

He only stumbled on the realization that the brain could reorganize its maps. And though he was not the first scientist to demonstrate neuroplasticity, it was through experiments he conducted early in his career that mainstream neuroscientists came to accept the plasticity of the brain.

To understand how brain maps can be changed, we need first to have a picture of them. They were first made vivid in human beings by the neurosurgeon Dr. Wilder Penfield at the Montreal Neurological Institute in the 1930s. For Penfield, "mapping" a patient's brain meant finding where in the brain different parts of the body were represented and their activities processed—a solid localization-ist project. Localizationists had discovered that the frontal lobes were the seat of the brain's motor system, which initiates and coordinates the movement of our muscles. The three lobes behind the frontal lobe, the temporal, parietal, and occipital lobes, comprise the brain's sensory system, processing the signals sent to the brain from our sense receptors—eyes, ears, touch receptors, and so on.

Penfield spent years mapping the sensory and motor parts of the brain, while performing brain surgery on cancer and epilepsy patients who could be conscious during the operation, because there are no pain receptors in the brain. Both the sensory and motor maps are part of the cerebral cortex, which lies on the brain's surface and so is easily accessible with a probe. Penfield discovered that when he touched a patient's sensory brain map with an electric probe, it triggered sensations that the patient felt in his body. He used the electric probe to help him distinguish the healthy tissue he wanted to preserve from the unhealthy tumors or pathological tissue he needed to remove.
Normally, when one's hand is touched, an electrical signal passes to the spinal cord and up to the brain, where it turns on cells in the

map that make the hand feel touched. Penfield found he could also make the patient feel his hand was touched by turning on the hand area of the brain map electrically. When he stimulated another part of the map, the patient might feel his arm being touched; another part, his face. Each time he stimulated an area, he asked his patients what they'd felt, to make sure he didn't cut away healthy tissue. After many such operations he was able to show where on the brain's sensory map all parts of the body's surface were represented.

He did the same for the motor map, the part of the brain that controls movement. By touching different parts of this map, he could trigger movements in a patient's leg, arm, face, and other muscles.

One of the great discoveries Penfield made was that sensory and motor brain maps, like geographical maps, are topographical, meaning that areas adjacent to each other on the body's surface are generally adjacent to each other on the brain maps. He also discovered that when he touched certain parts of the brain, he triggered long-lost childhood memories or dreamlike scenes—which implied that higher mental activities were also mapped in the brain.

The Penfield maps shaped several generations' view of the brain. But because scientists believed that the brain couldn't change, they assumed, and taught, that the maps were fixed, immutable, and universal—the same in each of us—though Penfield himself never made either claim.

Merzenich discovered that these maps are neither immutable within a single brain nor universal but vary in their borders and size from person to person. In a series of brilliant experiments he showed that the shape of our brain maps changes depending upon what we do over the course of our lives. But in order to prove this point he needed a tool far finer than Penfield's electrodes, one that would be able to detect changes in just a few neurons at a time.

While an undergraduate at the University of Portland, Merzenich and a friend used electronic lab equipment to demonstrate the storm of electrical activity in insects' neurons. These experiments came to the attention of a professor who admired Merzenich's talent and curiosity and recommended him for graduate school at both
Harvard and Johns Hopkins. Both accepted him. Merzenich opted for Hopkins to do his Ph.D. in physiology under one of the great neuroscientists of the time, Vernon Mountcastle, who in the 1950s was demonstrating that the subtleties of brain architecture could be discovered by studying the electrical activity of neurons using a new technique: micromapping with pm-shaped nikroledrodes.

Microelectrodes are so small and sensitive that they can be inserted inside or beside a single neuron and can detect when an individual neuron fires off its electrical signal to other neurons. The neuron's signal passes from the microelectrode to an amplifier and then to an oscilloscope screen, where it appears as a sharp spike. Merzenich would make most of his major discoveries with microelectrodes.

This momentous invention allowed neuroscientists to decode the communication of neurons, of which the adult human brain has approximately 100 billion. Using large electrodes as Penfield did, scientists could observe thousands of neurons firing at once. With microelectrodes, scientists could "listen in on" one or several neurons at a time as they communicated with one another. Micromapping is still about a thousand times more precise than the current generation of brain scans, which detect bursts of activity that last one second in thousands of neurons. But a neuron's electrical signal often lasts a thousandth of a second, so brain scans miss an extraordinary amount of information. Yet micromapping hasn't replaced brain scans because it requires an extremely tedious kind of surgery, conducted under a microscope with microsurgical instruments.

Merzenich took to this technology right away. To map the area of the brain that processes feeling from the hand, Merzenich would cut away a piece of a monkey's skull over the sensory cortex, exposing a 1- to 2-millimeter strip of brain, then insert a microelectrode beside a sensory neuron. Next, he would tap the monkey's hand until he touched a part—say, the tip of a finger—that caused that neuron to fire an electrical signal into the microelectrode. He would record the location of the neuron that represented the fingertip, establishing the first point on the map. Then he would remove the microelectrode, reinsert it near another neuron, and tap different parts of the hand, until he located the part that turned on that neuron. He did this until he'd mapped the entire hand. A single mapping might require five hundred insertions and take several days, and Merzenich and his colleagues did thousands of these laborious surgeries to make their discoveries.

At about this time, a crucial discovery was made that would forever affect Merzenich's work. In the 1960s, just as Merzenich was beginning to use microelectrodes on the brain, two other scientists, who had also worked at Johns Hopkins with Mountcastle, discovered that the brain in very young animals is plastic. David Hubel and Torsten Wiesel were micromapping the visual cortex to learn how vision is processed. They'd inserted microelectrodes into the visual cortex of kittens and discovered that different parts of the cortex processed the lines, orientations, and
movements of visually perceived objects. They also discovered that there was a “critical period,” from the third to the eighth week of life, when the newborn kitten's brain had to receive visual stimulation in order to develop normally. In the crucial experiment Hubel and Wiesel sewed shut one eyelid of a kitten during its critical period, so the eye got no visual stimulation. When they opened this shut eye, they found that the visual areas in the brain map that normally processed input from the shut eye had failed to develop, leaving the kitten blind in that eye for life. Clearly the brains of kittens during the critical period were plastic, their structure literally shaped by experience.

When Hubel and Wiesel examined the brain map for that blind eye, they made one more unexpected discovery about plasticity. The part of the kitten's brain that had been deprived of input from the shut eye did not remain idle. It had begun to process visual input from the open eye, as though the brain didn't want to waste any “cortical real estate” and had found a way to rewire itself—another indication that the brain is plastic in the critical period. For this work Hubel and Wiesel received the Nobel Prize. Yet even though they had discovered plasticity in infancy, they remained localizationists, defending the idea that the adult brain is hardwired by the end of infancy to perform functions in fixed locations.

The discovery of the critical period became one of the most famous in biology in the second half of the twentieth century. Scientists soon showed that other brain systems required environmental stimuli to develop. It also seemed that each neural system had a different critical period, or window of time, during which it was especially plastic and sensitive to the environment, and during which it had rapid, formative growth. Language development, for instance, has a critical period that begins in infancy and ends between eight years and puberty. After this critical period closes, a person's ability to learn a second language without an accent is limited. In fact, second languages learned after the critical period are not processed in the same part of the brain as is the native tongue.

The notion of critical periods also lent support to ethologist Konrad Lorenz's observation that goslings, if exposed to a human being for a brief period of time, between fifteen hours and three days after birth, bonded with that person, instead of with their mother, for life. To prove it, he got goslings to bond to him and follow him around. He called this process "imprinting." In fact, the psychological version of the critical period went back to Freud, who argued that we go through developmental stages that are brief windows of
time, during which we must have certain experiences to be healthy; these periods are formative, he said, and shape us for the rest of our lives.

Critical-period plasticity changed medical practice. Because of Hubel and Wiesel's discovery, children born with cataracts no longer faced blindness. They were now sent for corrective surgery as infants, during their critical period, so their brains could get the light required to form crucial connections. Microelectrodes had shown that plasticity is an indisputable fact of childhood. And they also seemed to show that, like childhood, this period of cerebral suppleness is short-lived.

Merzenich's first glimpse of adult plasticity was accidental. In 1968, after completing his doctorate, he went to do a postdoc with Clinton Woolsey, a researcher in Madison, Wisconsin, and peer of Penfield's. Woolsey asked Merzenich to supervise two neurosurgeons, Drs. Ron Paul and Herbert Goodman. The three decided to observe what happens in the brain when one of the peripheral nerves in the hand is cut and then starts to regenerate.

It is important to understand that the nervous system is divided into two parts. The first part is the central nervous system (the brain and spinal cord), which is the command-and-control center of the system; it was thought to lack plasticity. The second part is the peripheral nervous system, which brings messages from the sense receptors to the spinal cord and brain and carries messages from the brain and spinal cord to the muscles and glands. The peripheral nervous system was long known to be plastic; if you cut a nerve in your hand, it can "regenerate" or heal itself.

Each neuron has three parts. The dendrites are treelike branches that receive input from other neurons. These dendrites lead into the cell body, which sustains the life of the cell and contains its DNA. Finally the axon is a living cable of varying lengths (from microscopic lengths in the brain, to some that can run down to the legs and reach up to six feet long). Axons are often compared to wires because they carry electrical impulses at very high speeds (from 2 to 200 miles per hour) toward the dendrites of neighboring neurons.

A neuron can receive two kinds of signals: those that excite it and those that inhibit it. If a neuron receives enough excitatory signals
from other neurons, it will fire off its own signal. When it receives enough inhibitory signals, it becomes less likely to fire. Axons don't quite touch the neighboring dendrites. They are separated by a microscopic space called a synapse. Once an electrical signal gets to the end of the axon, it triggers the release of a chemical messenger, called a neurotransmitter, into the synapse. The chemical messenger floats over to the dendrite of the adjacent neuron, exciting or inhibiting it.

When we say that neurons "rewire" themselves, we mean that alterations occur at the synapse, strengthening and increasing, or weakening and decreasing, the number of connections between the neurons.

Merzenich, Paul, and Goodman wanted to investigate a well-known but mysterious interaction between the peripheral and central nervous systems. When a large peripheral nerve (which consists of many axons) is cut, sometimes in the process of regeneration the "wires get crossed." When axons reattach to the axons of the wrong nerve, the person may experience "false localization," so that a touch on the index finger is felt in the thumb. Scientists assumed that this false localization occurred because the regeneration process "shuffled" the nerves, sending the signal from the index finger to the brain map for the thumb.

The model scientists had of the brain and the nervous system was that each point on the body surface had a nerve that passed signals directly to a specific point on the brain map, anatomically hardwired at birth. Thus a nerve branch for the thumb always passed its signals directly to the spot on the sensory brain map for the thumb. Merzenich and the group accepted this "point-to-point" model of the brain map and innocently set out to document what was happening in the brain during this shuffling of nerves.

They micromapped the hand maps in the brains of several adolescent monkeys, cut a peripheral nerve to the hand, and immediately sewed the two severed ends close together but not quite touching, hoping the many axonal wires in the nerve would get crossed as the nerve regenerated itself. After seven months they remapped the brain. Merzenich assumed they would see a very disturbed, chaotic brain map. Thus, if the nerves for the thumb and the index finger had been crossed, he expected that touching the index finger would generate activity in the map area for the thumb. But he saw nothing of the kind. The map was almost normal.

"What we saw," says Merzenich, "was absolutely astounding. I couldn't understand it." It was topographically arranged as though the brain had unshuffled the signals from the crossed nerves.
This breakthrough week changed Merzenich's life. He realized that he, and mainstream neuroscience, had fundamentally misinterpreted how the human brain forms maps to represent the body and the world. If the brain map could normalize its structure in response to abnormal input, the prevailing view that we are born with a hardwired system had to be wrong. The brain had to be plastic.

How could the brain do it? Moreover, Merzenich also observed that the new topographical maps were forming in slightly different places than before. The localizationist view, that each mental function was always processed in the same location in the brain, had to be either wrong or radically incomplete. What was Merzenich to make of it?

He went back to the library to look for evidence that contradicted localizationism. He found that in 1912 Graham Brown and Charles Sherrington had shown that stimulating one point in the motor cortex might cause an animal to bend its leg at one time and straighten it at another. This experiment, lost in the scientific literature, implied that there was no point-to-point relationship between the brain's motor map and a given movement. In 1923 Karl Lashley, using equipment far cruder than microelectrodes, exposed a monkey's motor cortex, stimulated it in a particular place, and observed the resulting movement. He then sewed the monkey back up. After some time he repeated the experiment, stimulating the monkey in that same spot, only to find that the movement produced often changed. As Harvard's great historian of psychology of the time, Edwin G. Boring, put it, "One day's mapping would no longer be valid on the morrow."

Maps were dynamic.

Merzenich immediately saw the revolutionary implications of these experiments. He discussed the Lashley experiment with Vernon Mountcastle, a localizationist, who, Merzenich told me, "had actually been bothered by the Lashley experiment. Mountcastle did not instinctively want to believe in plasticity. He wanted things to be in their place, forever. And Mountcastle knew that this experiment represented an important challenge to how you think about the brain.

Mountcastle thought that Lashley was an extravagant exaggerator."
Neuroscientists were willing to accept Hubel and Wiesel's discovery that plasticity exists in infancy, because they accepted that the infant brain was in the midst of development. But they rejected Merzenich's discovery that plasticity continues into adulthood.

Merzenich leans back with an almost mournful expression and remembers, "I had all of these reasons why I wanted to believe that the brain wasn't plastic in this way, and they were thrown over in a week."

Merzenich now had to find his mentors among the ghosts of dead scientists, like Sherrington and Lashley. He wrote a paper on the shuffled nerve experiment, and in the discussion section he argued for several pages that the adult brain is plastic—though he didn't use the word.

But the discussion was never published. Clinton Woolsey, his supervisor, wrote a big X across it, saying that it was too conjectural and that Merzenich was going way beyond the data. When the paper was published, no mention was made of plasticity, and only minimal emphasis was given to explaining the new topographic organization. Merzenich backed down from the opposition, at least in print. He was still, after all, a postdoc working in another man's lab.

But he was angry, and his mind was churning. He was beginning to think that plasticity might be a basic property of the brain that had evolved to give humans a competitive edge and that it might be "a fabulous thing."

In 1971 Merzenich became a professor at the University of California at San Francisco, in the department of otolaryngology and physiology, which did research on diseases of the ear. Now his own boss, he began the series of experiments that would prove the existence of plasticity beyond a doubt. Because the area was still so controversial, he did his plasticity experiments in the guise of more acceptable research. Thus he spent much of the early 1970s mapping the auditory cortex of different species of animals, and he helped others invent and perfect the cochlear implant.

The cochlea is the microphone inside our ears. It sits beside the vestibular apparatus that deals with position sense and that was damaged in Cheryl, Bach-y-Rita's patient. When the external world produces sound, different frequencies vibrate different little hair cells within the cochlea. There are three thousand such hair cells, which convert the sound into patterns of electrical signals that travel down the auditory nerve into the auditory cortex. The micromap-pers discovered that in the auditory cortex, sound frequencies are
mapped "tonotopically." That is, they are organized like a piano: the lower sound frequencies are at one end, the higher ones at the other.

A cochlear implant is not a hearing aid. A hearing aid amplifies sound for those who have partial hearing loss due to a partially functioning cochlea that works well enough to detect some sound. Cochlear implants are for those who are deaf because of a profoundly damaged cochlea. The implant replaces the cochlea, transforming speech sounds into bursts of electrical impulses, which it sends to the brain. Because Merzenich and his colleagues could not hope to match the complexity of a natural organ with three thousand hair cells, the question was, could the brain, which had evolved to decode complex signals coming from so many hair cells, decode impulses from a far simpler device? If it could, it would mean that

the auditory cortex was plastic, capable of modifying itself and responding to artificial inputs. The implant consists of a sound receiver, a converter that translates sound into electrical impulses, and an electrode inserted by surgeons into the nerves that run from the ear to the brain.

In the mid-1960s some scientists were hostile to the very idea of cochlear implants. Some said the project was impossible. Others argued that they would put deaf patients at risk of further damage. Despite the risks, patients volunteered for implants. At first some heard only noise; others heard just a few tones, hisses, and sounds starting and stopping.

Merzenich's contribution was to use what he had learned from mapping the auditory cortex to determine the kind of input patients needed from the implant to be able to decode speech, and where to implant the electrode. He worked with communication engineers to design a device that could transmit complex speech on a small number of bandwidth channels and still be intelligible. They developed a highly accurate, multichannel implant that allowed deaf people to hear, and the design became the basis for one of the two primary cochlear implant devices available today.

What Merzenich most wanted, of course, was to investigate plasticity directly. Finally, he decided to do a simple, radical experiment in which he would cut off all sensory input to a brain map and see how it responded. He went to his friend and fellow neuroscientist Jon Kaas, of Vanderbilt University in Nashville, who worked with adult monkeys. A monkey's hand, like a human's, has three main nerves: the radial, the median, and the ulnar. The *median* nerve conveys sensation mostly from the *middle* of the hand, the other two from either side of the hand. Merzenich cut the median nerve in one of the monkeys to see how the median nerve brain map would respond when *all* input was cut off. He went back to San Francisco and waited.
Two months later he returned to Nashville. When he mapped the monkey, he saw, as he expected, that the portion of the brain map that serves the median nerve showed no activity when he touched the middle part of the hand. But he was shocked by something else.

When he stroked the outsides of the monkey's hand—the areas that send their signals through the radial and ulnar nerves—the median nerve map lit up! The brain maps for the radial and ulnar nerves had almost doubled in size and invaded what used to be the median nerve map. And these new maps were topographical. This time he and Kaas, writing up the findings, called the changes "spectacular" and used the word "plasticity" to explain the change, though they put it in quotes.

The experiment demonstrated that if the median nerve was cut, other nerves, still brimming with electrical input, would take over the unused map space to process their input. When it came to allocating brain-processing power, brain maps were governed by competition for precious resources and the principle of use it or lose it.

The competitive nature of plasticity affects us all. There is an endless war of nerves going on inside each of our brains. If we stop exercising our mental skills, we do not just forget them: the brain map space for those skills is turned over to the skills we practice instead. If you ever ask yourself, "How often must I practice French, or guitar, or math to keep on top of it?" you are asking a question about competitive plasticity. You are asking how frequently you must practice one activity to make sure its brain map space is not lost to another.

Competitive plasticity in adults even explains some of our limitations. Think of the difficulty most adults have in learning a second language. The conventional view now is that the difficulty arises because the critical period for language learning has ended, leaving us with a brain too rigid to change its structure on a large scale. But the discovery of competitive plasticity suggests there is more to it. As we age, the more we use our native language, the more it comes to dominate our linguistic map space. Thus it is also because our brain is plastic—and because plasticity is competitive—that it is so hard to learn a new language and end the tyranny of the mother tongue.

But why, if this is true, is it easier to learn a second language when we are young? Is there not competition then too? Not really, If two languages are learned at the same time, during the critical period, both get a foothold. Brain scans, says Merzenich, show that in a
bilingual child all the sounds of its two languages share a single large map, a library of sounds from both languages.

Competitive plasticity also explains why our bad habits are so difficult to break or "unlearn." Most of us think of the brain as a container and learning as putting something in it. When we try to break a bad habit, we think the solution is to put something new into the container. But when we learn a bad habit, it takes over a brain map, and each time we repeat it, it claims more control of that map and prevents the use of that space for "good" habits. That is why "unlearning" is often a lot harder than learning, and why early childhood education is so important—it's best to get it right early, before the "bad habit" gets a competitive advantage.

Merzenich's next experiment, ingeniously simple, made plasticity famous among neuroscientists and eventually did more to win over skeptics than any plasticity experiment before or since.

He mapped a monkey's hand map in the brain. Then he amputated the monkey's middle finger. After a number of months he remapped the monkey and found that the brain map for the amputated finger had disappeared and that the maps for the adjacent fingers had grown into the space that had originally mapped for the middle finger. Here was the clearest possible demonstration that brain maps are dynamic, that there is a competition for cortical real estate, and that brain resources are allocated according to the principle of use it or lose it.

Merzenich also noticed that animals of a particular species may have similar maps, but they are never identical. Micromapping allowed him to see differences that Penfield, with larger electrodes, could not. He also found that the maps of normal body parts change every few weeks. Every time he mapped a normal monkey's face, it was unequivocally different. Plasticity doesn't require the provocation of cut nerves or amputations. Plasticity is a normal phenomenon, and brain maps are constantly changing. When he wrote up this new experiment, Merzenich finally took the word "plasticity" out of quotes. Yet despite the elegance of his experiment, opposition to Merzenich's ideas did not melt away overnight.

He laughs when he says it. "Let me tell you what happened when I began to declare that the brain was plastic. I received hostile treatment. I don't know how else to put it. I got people saying things in reviews such as, 'This would be really interesting if it could possibly be true, but it could not be.' It was as if I just made it up."

Because Merzenich was arguing that brain maps could alter their borders and location and change their functions well into adulthood, localizationists opposed him. "Almost everybody I knew in the mainstream of neuroscience," he says, "thought that this was sort of semi-serious stuff—that the experiments were sloppy, that the effects described were uncertain. But actually the experiment had been done enough times that I realized that the position of the majority was arrogant and indefensible."
One of the major figures who voiced doubts was Torsten Wiesel. Despite the fact that Wiesel had shown that plasticity exists in the critical period, he still opposed the idea that it existed in adults, and wrote that he and Hubel “firmly believed that once cortical connections were established in their mature form, they stayed in place permanently.” He had indeed won the Nobel Prize for establishing where visual processing occurs, a finding considered one of localizationism's greatest triumphs. Wiesel now accepts adult plasticity and has gracefully acknowledged in print that for a long time he was wrong and that Merzenich’s pioneering experiments ultimately led him and his colleagues to change their minds, Hardcore localizationists took notice when a man of Wiesel’s stature changed his mind. "The most frustrating thing," says Merzenich, "was that I saw that neuroplasticity had all kinds of potential implications for medical therapeutics—for the interpretation of human neuropathology and psychiatry. And nobody paid any attention."

Since plastic change is a process, Merzenich realized he would only really be able to understand it if he could see it unfolding in the brain over time. He cut a monkey's median nerve and then did multiple mappings over a number of months.

The first mapping, immediately after he cut the nerve, showed, as he expected, that the brain map for the median nerve was completely silent when the middle of the hand was stroked. But when he stroked the part of the hand served by the outside nerves, the silent median nerve portion of the map lit up immediately. Maps for the outside nerves, the radial and ulnar nerves, now appeared in the median map space. These maps sprang up so quickly, it was as though they had been hidden there all along, since early development, and now they were "unmasked."

On the twenty-second day Merzenich mapped the monkey again. The radial and ulnar maps, which had been lacking in detail when they first appeared, had grown more refined and detailed and had now expanded to occupy almost the entire median nerve map. (A primitive map lacks detail; a refined map has a lot and thus conveys more information.)

By the 144th day the whole map was every bit as detailed as a normal map.

By doing multiple mappings over time, Merzenich observed that the new maps were changing their borders, becoming more detailed, and even moving around the brain. In one case he even saw a map disappear altogether, like Atlantis.
It seemed reasonable to assume that if totally new maps were forming, then new connections must have been forming among neurons. To help understand this process, Merzenich invoked the ideas of Donald O. Hebb, a Canadian behavioral psychologist who had worked with Penfield. In 1949 Hebb proposed that learning linked neurons in new ways. He proposed that when two neurons fire at the same time repeatedly (or when one fires, causing another to fire), chemical changes occur in both, so that the two tend to connect more strongly. Hebb's concept—actually proposed by Freud sixty years before—was neatly summarized by neuroscientist Carla Shatz: Neurons that fire together wire together.

Hebb's theory thus argued that neuronal structure can be altered by experience. Following Hebb, Merzenich’s new theory was that neurons in brain maps develop strong connections to one another when they are activated at the same moment in time. And if maps could change, thought Merzenich, then there was reason to hope that people born with problems in brain map-processing areas—people with learning problems, psychological problems, strokes, or brain injuries—might be able to form new maps if he could help them form new neuronal connections, by getting their healthy neurons to fire together and wire together.

Starting in the late 1980s, Merzenich designed or participated in brilliant studies to test whether brain maps are time based and whether their borders and functioning can be manipulated by "playing" with the timing of input to them.

In one ingenious experiment, Merzenich mapped a normal monkey's hand, then sewed together two of the monkey's fingers, so that both fingers moved as one. After several months of allowing the monkey to use its sewn fingers, the monkey was remapped. The two maps of the originally separate fingers had now merged into a single map. If the experimenters touched any point on either finger, this new single map would light up. Because all the movements and sensations in those fingers always occurred simultaneously, they'd formed the same map. The experiment showed that timing of the input to the neurons in the map was the key to forming it—neurons that fired together in time wired together to make one map.

Other scientists tested Merzenich’s findings on human beings.

Some people are born with their fingers fused, a condition called syndactyly or "webbed-finger syndrome." When two such people were mapped, the brain scan found that they each had one large map for their fused fingers instead of two separate ones.
After surgeons separated the webbed fingers, the subjects' brains were remapped, and two distinct maps emerged for the two separated digits. Because the fingers could move independently, the neurons no longer fired simultaneously, illustrating another principle of plasticity: if you separate the signals to neurons in time, you create separate brain maps. In neuroscience this finding is now summarized as Neurons that fire apart wire apart—or Neurons out of sync fail to link.

In the next experiment in the sequence, Merzenich created a map for what might be called a nonexistent finger that ran perpendicular to the other fingers. The team stimulated all five fingertips of a monkey simultaneously, five hundred times a day for over a month, preventing the monkey from using its fingers one at a time. Soon the monkey's brain map had a new, elongated finger map, in which the five fingertips were merged. This new map ran perpendicular to the other fingers, and all the fingertips were part of it, instead of part of their individual finger maps, which had started to melt away from disuse.

In the final and most brilliant demonstration, Merzenich and his team proved that maps cannot be anatomically based. They took a small patch of skin from one finger, and—this is the key point—with the nerve to its brain map still attached, surgically grafted the skin onto an adjacent finger. Now that piece of skin and its nerve were stimulated whenever the finger it was attached to was moved or touched in the course of daily use. According to the anatomical-hardwiring model, the signals should still have been sent from the skin along its nerve to the brain map for the finger that the skin and nerve originally came from. Instead, when the team stimulated the patch of skin, the map of its new finger responded. The map for the patch of skin migrated from the brain map of the original finger to its new one, because both the patch and the new finger were stimulated simultaneously.

In a few short years Merzenich had discovered that adult brains are plastic, persuaded skeptics in the scientific community this was the case, and shown that experience changes the brain. But he still hadn't explained a crucial enigma: how the maps organize themselves to become topographical and function in a way that is useful to us.

When we say a brain map is organized topographically, we mean that the map is ordered as the body itself is ordered. For instance, our middle finger sits between our index finger and our ring finger. The same is true for our brain map: the map for the middle finger sits between the map for our index finger and that of our ring finger.

Topographical organization is efficient, because it means that parts of the brain that often work together are close together in the brain map, so signals don't have to travel far in the brain itself.
The question for Merzenich was, how does this topographic order emerge in the brain map? The answer he and his group came to was ingenious. A topographic order emerges because many of our everyday activities involve repeating sequences in a fixed order.

When we pick up an object the size of an apple or baseball, we usually grip it first with our thumb and index finger, then wrap the rest of our fingers around it one by one. Since the thumb and index finger often touch at almost the same time, sending their signals to the brain almost simultaneously, the thumb map and the index finger map tend to form close together in the brain. (Neurons that fire together wire together.) As we continue to wrap our hand around the object, our middle finger will touch it next, so its brain map will tend to be beside the index finger and farther away from the thumb. As this common grasping sequence—thumb first, index finger second, middle finger third—is repeated thousands of times, it leads to a brain map where the thumb map is next to the index finger map, which is next to the middle finger map, and so on. Signals that tend to arrive at separate times, like thumbs and pinkies, have more distant brain maps, because neurons that fire apart wire apart.

Many if not all brain maps work by spatially grouping together events that happen together. As we have seen, the auditory map is arranged like a piano, with mapping regions for low notes at one end and for high notes at the other. Why is it so orderly? Because the low frequencies of sounds tend to come together with one another in nature. When we hear a person with a low voice, most of the frequencies are low, so they get grouped together.

The arrival of Bill Jenkins at Merzenich's lab ushered in a new phase of research that would help Merzenich develop practical applications of his discoveries. Jenkins, trained as a behavioral psychologist, was especially interested in understanding how we learn. He suggested they teach animals to learn new skills, to observe how learning affected their neurons and maps.

In one basic experiment they mapped a monkey's sensory cortex. Then they trained it to touch a spinning disk with its fingertip, with just the right amount of pressure for ten seconds to get a banana-pellet reward. This required the monkey to pay close attention, learning to touch the disk very lightly and judge time accurately. After thousands of trials, Merzenich and Jenkins remapped the monkey's brain and saw that the area mapping the monkey's fingertip had enlarged as the monkey had learned how to touch the
disk with the right amount of pressure. The experiment showed that when an animal is motivated to learn, the brain responds plastically.

The experiment also showed that as brain maps get bigger, the individual neurons get more efficient in two stages. At first, as the monkey trained, the map for the fingertip grew to take up more space. But after a while individual neurons within the map became more efficient, and eventually fewer neurons were required to perform the task.

When a child learns to play piano scales for the first time, he tends to use his whole upper body—wrist, arm, shoulder—to play each note. Even the facial muscles tighten into a grimace. With practice the budding pianist stops using irrelevant muscles and soon uses only the correct finger to play the note. He develops a "lighter touch," and if he becomes skillful, he develops "grace" and relaxes when he plays. This is because the child goes from using a massive number of neurons to an appropriate few, well matched to the task. This more efficient use of neurons occurs whenever we become proficient at a skill, and it explains why we don't quickly run out of map space as we practice or add skills to our repertoire.

Merzenich and Jenkins also showed that individual neurons got more selective with training. Each neuron in a brain map for the sense of touch has a "receptive field," a segment on the skin's surface that "reports" to it. As the monkeys were trained to feel the disk, the receptive fields of individual neurons got smaller, firing only when small parts of the fingertip touched the disk. Thus, despite the fact that the size of the brain map increased, each neuron in the map became responsible for a smaller part of the skin surface, allowing the animal to have finer touch discrimination. Overall, the map became more precise.

Merzenich and Jenkins also found that as neurons are trained and become more efficient, they can process faster. This means that the speed at which we think is itself plastic. Speed of thought is essential to our survival. Events often happen quickly, and if the brain is slow, it can miss important information. In one experiment, Merzenich and Jenkins successfully trained monkeys to distinguish sounds in shorter and shorter spans of time. The trained neurons fired more quickly in response to the sounds, processed them in a
shorter time, and needed less time to "rest" between firings. Faster neurons ultimately lead to faster thought—no minor matter—because speed of thought is a crucial component of intelligence. IQ tests, like life, measure not only whether you can get the right answer but how long it takes you to get it.

They also discovered that as they trained an animal at a skill, not only did its neurons fire faster, but because they were faster their signals were dearer, Faster neurons were more likely to fire in sync with each other—becoming better team players—wiring together more and forming groups of neurons that gave off clearer and more powerful signals. This is a crucial point, because a powerful signal has greater impact on the brain. When we want to remember something we have heard we must hear it clearly, because a memory can be only as clear as its original signal.

Finally, Merzenich discovered that paying close attention is essential to long-term plastic change. In numerous experiments he found that lasting changes occurred only when his monkeys paid close attention. When the animals performed tasks automatically, without paying attention, they changed their brain maps, but the changes did not last. We often praise "the ability to multitask." While you can learn when you divide your attention, divided attention doesn't lead to abiding change in your brain maps.

When Merzenich was a boy, his mother's first cousin, a grade-school teacher in Wisconsin, was chosen teacher of the year for the entire United States. After the ceremony at the White House, she visited the Merzenich family in Oregon.

"My mother," he recalls, "asked the inane question that you'd ask in conversation: 'What are your most important principles in teaching?' And her cousin answered, 'Well, you test them when they come into school, and you figure out whether they are worthwhile. And if they are worthwhile, you really pay attention to them, and you don't waste time on the ones that aren't.' That's what she said. And you know, in one way or another, that's reflected in how people have treated children who are different, forever. It's just so destructive to imagine that your neurological resources are permanent and enduring and cannot be substantially improved and altered."

Merzenich now became aware of the work of Paula Tallal at Rutgers, who had begun to analyze why children have trouble learning to read. Somewhere between 5 and 10 percent of preschool children have a language disability that makes it difficult for them to read, write, or even follow instructions. Sometimes these children are called dyslexic.
Babies begin talking by practicing consonant-vowel combinations, cooing "da, da, da" and "ba, ba, ba." In many languages their first words consist of such combinations. In English their first words are often "mama" and "dada," "pee pee," and so on. Tallal's research showed that children with language disabilities have auditory processing problems with common consonant-vowel combinations that are spoken quickly and are called "the fast parts of speech." The children have trouble hearing them accurately and, as a result, reproducing them accurately.

Merzenich believed that these children's auditory cortex neurons were firing too slowly, so they couldn't distinguish between two very similar sounds or be certain, if two sounds occurred close together, which was first and which was second. Often they didn't hear the beginnings of syllables of the Sound changes within syllables. Normally neurons, after they have processed a sound, are ready to fire again after about a 30-millisecond rest. Eighty percent of language-impaired children took at least three times that long, so that they lost large amounts of language information. When their neuron-firing patterns were examined, the signals weren't clear.

"They were muddy in, muddy out," says Merzenich. Improper hearing led to weaknesses in all the language tasks, so they were weak in vocabulary, comprehension, speech, reading, and writing. Because they spent so much energy decoding words, they tended to use shorter sentences and failed to exercise their memory for longer sentences.

Their language processing was more childlike, or "delayed," and they still needed practice distinguishing "da, da, da" and "ba, ba, ba."

When Tallal originally discovered their problems, she feared that "these kids were 'broken,' and there was nothing you could do" to fix their basic brain defect. But that was before she and Merzenich combined forces.

In 1996 Merzenich, Paula Tallal, Bill Jenkins, and one of Tallal's colleagues, psychologist Steve Miller, formed the nucleus of a company, Scientific Learning, that is wholly devoted to using neuro-plastic research to help people rewire their brains.

Their head office is in the Rotunda, a Beaux Arts masterpiece with an elliptical glass dome, 120 feet high, its edges painted in 24-karat gold leaf, in the middle of downtown Oakland, California. When you enter, you enter another world. The Scientific Learning staff includes child psychologists, plasticity researchers,
experts in human motivation, speech pathologists, engineers, programmers, and animators. From their desks these researchers, bathed in natural light, can look up into the gorgeous dome.

*Fast ForWord* is the name of the training program they developed for language-impaired and learning-disabled children. The program exercises every basic brain function involved in language from decoding sounds up to comprehension—a kind of cerebral cross-training.

The program offers seven brain exercises. One teaches the children to improve their ability to distinguish short sounds from long. A cow flies across the computer screen, making a series of mooing sounds. The child has to catch the cow with the computer cursor and hold it by depressing the mouse button. Then suddenly the length of the moo sound changes subtly. At this point the child must release the cow and let it fly away. A child who releases it just after the sound changes scores points. In another game children learn to identify easily confused consonant-vowel combinations, such as "ba" and "da," first at slower speeds than they occur in normal language, and then at increasingly faster speeds. Another game teaches the children to hear faster and faster frequency glides (sounds like "whooooop" that sweep up). Another teaches them to remember and match sounds. The "fast parts of speech" are used throughout the exercises but have been slowed down with the help of computers, so the language-disabled children can hear them and develop clear maps for them; then gradually, over the course of the exercises, they are sped up. Whenever a goal is achieved, something funny happens: the character in the animation eats the answer, gets indigestion, gets a funny look on its face, or makes some slapstick move that is unexpected enough to keep the child attentive. This "reward" is a crucial feature of the program, because each time the child is rewarded, his brain secretes such neurotransmitters as dopamine and acetylcholine, which help consolidate the map changes he has just made. (Dopamine reinforces the reward, and acetylcholine helps the brain "tune in" and sharpen memories.)

Children with milder difficulties typically work at *Fast ForWord* for an hour and forty minutes a day, five days a week for several weeks, and those with more severe difficulties work for eight to twelve weeks.

The first study results, reported in the journal *Science* in January 1996, were remarkable. Children with language impairments were divided into two groups, one that did *Fast ForWord* and a control group that did a computer game that was similar but didn't train temporal processing or use modified speech. The two groups were matched for age, IQ, and language-processing skills. The children who did *Fast ForWord* made significant progress on standard speech, language, and auditory-processing tests, ended up with normal or better-than-normal language scores, and kept their gains when re-tested six weeks after training. They improved far more than children in the control group.
Further study followed five hundred children at thirty-five sites—hospitals, homes, and clinics. All were given standardized language tests before and after Fast ForWord training. The study showed that most children's ability to understand language normalized after Fast ForWord. In many cases, their comprehension rose above normal.

The average child who took the program moved ahead 1.8 years of language development in six weeks, remarkably fast progress. A Stanford group did brain scans of twenty dyslexic children, before and after Fast ForWord. The opening scans showed that the children used different parts of their brains for reading than normal children do. After Fast ForWord new scans showed that their brains had begun to normalize. (For instance, they developed increased activity, on average, in the left temporo-parietal cortex, and their scans began to show patterns that were similar to those of children who have no reading problems.)

Willy Arbor is a seven-year-old from West Virginia. He's got red hair and freckles, belongs to Cub Scouts, likes going to the mall, and, though barely over four feet tall, loves wrestling. He's just gone through Fast ForWord and has been transformed.

"Willy's main problem was hearing the speech of others clearly," his mother explains. "I might say the word 'copy' and he would think I said 'coffee.' If there was any background noise, it was especially hard for him to hear. Kindergarten was depressing. You could see his insecurity. He got into nervous habits like chewing on his clothes, or his sleeve, because everybody else was getting the answer right, and he wasn't. The teacher had actually talked about holding him back in first grade." Willy had trouble reading, both to himself and aloud.

"Willy," his mother continues, "couldn't hear change in pitch properly. So he couldn't tell when a person was making an exclamation or just a general statement, and he didn't grasp inflections in speech, which made it hard for him to read people's emotions. Without the high and low pitch he wasn't hearing that wow when people are excited. It was like everything was the same."

Willy was taken to a hearing specialist, who diagnosed his "hear-
upstairs—put them in the closet—then come down for dinner,’ he'd forget them. He'd take his shoes off, go up the steps, and ask 'Mom what did you want me to do?’ Teachers had to repeat instructions all the time." Though he appeared to be a gifted child—he was good at math—his problems held him back in that area too.

His mother protested making Willy repeat first grade and over the summer sent him to Fast ForWord for eight weeks.

"Before he did Fast ForWord," his mother recalls, "you'd put him at the computer, and he got very stressed out. With this program, though, he spent a hundred minutes a day for a solid eight weeks at the computer. He loved doing it and loved the scoring because he could see himself going up, up, up," says his mother. As he improved, he became able to perceive inflections in speech, got better at reading the emotions of others, and became a less anxious child. "So much changed for him. When he brought his midterms home, he said, It is better than last year, Mommy.’ He began bringing home A and B marks on his papers most of the time—a noticeable difference ... Now it's 'I can do this. This is my grade. I can make it better.' I feel like I had my prayer answered, it's done so much for him.

It's amazing." A year later he continues to improve.

**Merzenich's team started hearing that Fast ForWord was**

having a number of spillover effects. Children's handwriting improved. Parents reported that many of the students were starting to show sustained attention and focus. Merzenich thought these surprising benefits were occurring because Fast ForWord led to some general improvements in mental processing.

One of the most important brain activities—one we don't often think about—is the determination of how long things go on, or

temporal processing. You can't move properly, perceive properly, or predict properly if you can't determine how long events last. Merzenich discovered that when you train people to distinguish very fast vibrations on their skin, lasting only 75 milliseconds, these same people could detect 75-millisecond sounds as well. It seemed that Fast ForWord was improving the brain's general ability to keep time. Sometimes these improvements spilled over into visual processing as well. Before Fast ForWord, when Willy was given a game that asked which items are out of place—a boot up in the tree, or a tin can on the roof—his eyes jumped all over the page. He was trying to see the
whole page instead of taking in a little section at a time. At school he skipped lines when he read. After Fast ForWord his eyes no longer jumped around the page, and he was able to focus his visual attention.

A number of children who took standardized tests shortly after completing Fast ForWord showed improvements not only in language, speaking, and reading, but in math, science, and social studies as well. Perhaps these children were hearing what was going on in class better or were better able to read—but Merzenich thought it might be more complicated.

"You know," he says, "IQ goes up. We used the matrix test, which is a visual-based measurement of IQ—and IQ goes up."

The fact that a visual component of the IQ went up meant that the IQ improvements were not caused simply because Fast ForWord improved the children's ability to read verbal test questions. Their mental processing was being improved in a general way, possibly because their temporal processing was improving. And there were other unexpected benefits. Some children with autism began to make some general progress.

The mystery of autism—a human mind that cannot conceive of other minds—is one of the most baffling and poignant in psychiatry and one of the most severe developmental disorders of childhood. It is called a "pervasive developmental disorder," because so many aspects of development are disturbed: intelligence, perception, socializing skills, language, and emotion.

Most autistic children have an IQ of less than 70. They have major problems connecting socially to others and may, in severe cases, treat people like inanimate objects, neither greeting them nor acknowledging them as human beings. At times it seems that autistics don't have a sense that "other minds" exist in the world. They also have perceptual processing difficulties and are thus often hypersensitive to sound and touch, easily overloaded by stimulation. (That may be one reason autistic children often avoid eye contact: the stimulation from people, especially when coming from many senses at once, is too intense.) Their neural networks appear to be overactive, and many of these children have epilepsy.

Because so many autistic children have language impairments, clinicians began to suggest the Fast ForWord program for them. They never anticipated what might happen. Parents of autistic children who did Fast ForWord told Merzenich that their children became more connected socially. He began asking, were the children simply being trained to be more attentive listeners? And he was fascinated by the fact that with Fast ForWord both the language symptoms and the autistic symptoms seemed to be fading together. Could this mean that the language and autistic problems were different expressions of a common problem?
Two studies of autistic children confirmed what Merzenich had been hearing. One, a language study, showed that *Fast ForWord* quickly moved autistic children from severe language impairment to the normal range. But another pilot study of one hundred autistic children showed that *Fast ForWord* had a significant impact on their autistic symptoms as well. Their attention spans improved. Their sense of humor improved. They became more connected to people. They developed better eye contact, began greeting people and addressing them by name, spoke with them, and said good-bye at the end of their encounters. It seemed the children were beginning to experience the world as filled with other human minds.

**Lauralee, an eight-year-old autistic girl, was diagnosed**

with moderate autism when she was three. Even as an eight-year-old she rarely used language. She didn't answer to her name, and to her parents, it seemed she was not hearing it. Sometimes she would speak, but when she did, "she had her own language," says her mother, "which was often unintelligible," If she wanted juice, she didn't ask for it. She would make gestures and pull her parents over to the cabinets to get things for her. She had other autistic symptoms, among them the repetitive movements that autistic children use to try to contain their sense of being overwhelmed. According to her mother, Lauralee had "the whole works—the flapping of the hands, toe-walking, a lot of energy, biting. And she couldn't tell me what she was feeling."

She was very attached to trees. When her parents took her walking in the evening to burn off energy, she'd often stop, touch a tree, hug it, and speak to it.

Lauralee was unusually sensitive to sounds. "She had bionic ears," says her mother. "When she was little, she would often cover her ears. She couldn't tolerate certain music on the radio, like classical and slow music." At her pediatrician's office she heard sounds from the floor upstairs that others didn't. At home she would go over to the sinks, fill them with water, then wrap herself around the pipes, hugging them, listening to the water drain through them.

Lauralee's father is in the navy and served in the Iraq war in 2003. When the family was transferred to California, Lauralee was enrolled in a public school with a special-ed class that used *Fast For-Word*. The program took her about two hours a day for eight weeks to complete.

When she finished it, "she had an explosion in language," says her mother, "and began to speak more and use complete sentences. She could tell me about her days at school. Before I would just say, Did you have a good day or a bad day?"
Now she was able to say what she did, and she remembered details. If she got into a bad situation, she would be able to tell me, and I wouldn’t have to prompt her to get it out of her. She also found it easier to remember things.” Lauralee has always loved to read, but now she is reading longer books, non-fiction and the encyclopedia. "She is listening to quieter sounds now and can tolerate different sounds from the radio," says her mother. "It was an awakening for her. And with the better communication, there was an awakening for all of us. It was a big blessing."

Merzenich decided that to deepen his understanding of autism and its many developmental delays, he would have to go back to the lab. He thought the best way to go about it was first to produce an "autistic animal"—one that had multiple developmental delays, as autistic children do. Then he could study it and try to treat it.

As Merzenich began to think through what he calls the "infantile catastrophe" of autism, he had a hunch that something might be going wrong in infancy, when most critical periods occur, plasticity is at its height, and a massive amount of development should be occurring. But autism is largely an inherited condition. If one identical twin is autistic, there is an 80 to 90 percent chance the other twin will be as well. In cases of nonidentical twins, where one is autistic, the nonautistic twin will often have some language and social problems.

Yet the incidence of autism has been climbing at a staggering rate that can’t be explained by genetics alone. When the condition was first recognized over forty years ago, about one in 5,000 people had it. Now it is fifteen in 5,000. That number has risen partly because autism is more often diagnosed, and because some children are labeled mildly autistic to get public funding for treatment. "But" says Merzenich, "even when all of the corrections are made by very hard-assed epidemiologists, it looks like it's about a threefold increase over the last fifteen years. There is a world emergency that relates to risk factors for autism."

He has come to think it likely that an environmental factor affects the neural circuits in these children, forcing the critical periods to shut down early, before the brain maps are fully differentiated. When we are born, our brain maps are often "rough drafts," or sketches, lacking detail, undifferentiated. In the critical period, when the structure of our brain maps is literally getting shaped by our first worldly experiences, the rough draft normally becomes detailed and differentiated,
Merzenich and his team used micromapping to show how maps in newborn rats are formed in the critical period. Right after birth, at

the beginning of the critical period, auditory maps were undifferentiated, with only two broad regions in the cortex. Half of the map responded to any high-frequency sound. The other half responded to any low-frequency sound.

When the animal was exposed to a particular frequency during the critical period, that simple organization changed. If the animal was repeatedly exposed to a high C, after a while only a few neurons would turn on, becoming selective for high C. The same would happen when the animal was exposed to a D, E, F, and so on. Now the map, instead of having two broad areas, had many different areas, each responding to different notes. It was now differentiated.

What is remarkable about the cortex in the critical period is that it is so plastic that its structure can be changed just by exposing it to new stimuli. That sensitivity allows babies and very young children in the critical period of language development to pick up new sounds and words effortlessly, simply by hearing their parents speak; mere exposure causes their brain maps to wire in the changes. After the critical period older children and adults can, of course, learn languages, but they really have to work to pay attention. For Merzenich, the difference between critical-period plasticity and adult plasticity is that in the critical period the brain maps can be changed just by

being exposed to the world because "the learning machinery is continuously on."

It makes good biological sense for this "machinery" always to be on because babies can't possibly know what will be important in life, so they pay attention to everything. Only a brain that is already

ewhat organized can sort out what is worth paying attention to.

The next clue Merzenich needed in order to understand autism came from a line of research that was originated during the Second World War, in Fascist Italy, by a young Jewish woman, Rita Levi-Montalcini, while in hiding. Levi-Montalcini was born in Turin in 1909 and attended medical school there. In 1938, when Mussolini barred Jews from practicing medicine and doing scientific research, she fled to Brussels to continue her studies; when the Nazis threatened Belgium, she went back to Turin and built a secret laboratory in her bedroom, to study how nerves form, forging microsurgical equipment from sewing needles. When the Allies bombed Turin in 1940, she fled to Piedmont. One day in 1940, traveling to a small northern Italian village in a cattle car that had been converted into a passenger train, she sat down on the floor and read a scientific paper by Viktor Hamburger, who had been doing pioneering work on the development of neurons by studying chick embryos. She decided to repeat and extend his experiments, working on a table in a mountain house with eggs from a local farmer. When she finished each
experiment, she ate the eggs. After the war Hamburger invited Levi-Montalcini to join him and his researchers in St. Louis to work on their discovery that the nerve fibers of chicks grew faster in the presence of tumors from mice. Levi-Montalcini speculated that the tumor might be releasing a substance to promote nerve growth. With biochemist Stanley Cohen she isolated the protein responsible and called it nerve growth factor, or NGF. Levi-Montalcini and Cohen were awarded the Nobel Prize in 1986.

Levi-Montalcini's work led to the discovery of a number of such nerve growth factors, one of which, brain-derived neurotrophic factor, or BDNF, caught Merzenich's attention.

BDNF plays a crucial role in reinforcing plastic changes made in the brain in the critical period. According to Merzenich, it does this in four different ways.

When we perform an activity that requires specific neurons to fire together, they release BDNF. This growth factor consolidates the connections between those neurons and helps to wire them together so they fire together reliably in the future. BDNF also promotes the growth of the thin fatty coat around every neuron that speeds up the transmission of electrical signals.

During the critical period BDNF turns on the nucleus basalis, the part of our brain that allows us to focus our attention—and keeps it on, throughout the entire critical period. Once turned on, the nucleus basalis helps us not only pay attention but remember what we are experiencing. It allows map differentiation and change to take place effortlessly. Merzenich told me, "It is like a teacher in the brain saying, 'Now this is really important—this you have to know for the exam of life.'" Merzenich calls the nucleus basalis and the attention system the "modulatory control system of plasticity"—the neurochemical system that, when turned on, puts the brain in an extremely plastic state. The fourth and final service that BDNF performs—when it has completed strengthening key connections—is to help close down the critical period. Once the main neuronal connections are laid down, there is a need for stability and hence less plasticity in the system. When BDNF is released in sufficient quantities, it turns off the nucleus basalis and ends that magical epoch of effortless learning. Henceforth the nucleus can be activated only when something important, surprising, or novel occurs, or if we make the effort to pay close attention.
Merzenich's work on the critical period and BDNF helped him develop a theory that explains how so many different problems could be part of a single autistic whole. During the critical period, he argues, some situations overexcite the neurons in children who have genes that predispose them to autism, leading to the massive, premature release of BDNF. Instead of important connections being reinforced, all connections are. So much BDNF is released that it turns off the critical period prematurely, sealing all these connections in place, and the child is left with scores of undifferentiated brain maps and hence pervasive developmental disorders. Their brains are hyperexcitable and hypersensitive. If they hear one frequency, the whole auditory cortex starts firing. This is what seemed to be happening in Lauralee, who had to cover her "bionic" ears when she heard music. Other autistic children are hypersensitive to touch and feel tormented when the labels in their clothes touch their skin. Merzenich's theory also explains the high rates of epilepsy in autism: because of BDNF release, the brain maps are poorly differentiated, and because so many connections in the brain have been indiscriminately reinforced, once a few neurons start firing, the whole brain can be set off. It also explains why autistic children have bigger brains—the substance increases the fatty coating around the neurons.

If BDNF release was contributing to autism and language problems, Merzenich needed to understand what might cause young neurons to get "overexcited" and release massive amounts of the chemical.

Several studies alerted him to how an environmental factor might contribute. One disturbing study showed that the closer children lived to the noisy airport in Frankfurt, Germany, the lower their intelligence was. A similar study, on children in public housing high-rises above the Dan Ryan Expressway in Chicago, found that the closer their floor was to the highway, the lower their intelligence. So Merzenich began wondering about the role of a new environmental risk factor that might affect everyone but have a more damaging effect on genetically predisposed children; the continuous background noise from machines, sometimes called white noise. White noise consists of many frequencies and is very stimulating to the auditory cortex.

"Infants are reared in continuously more noisy environments. There is always a din," he says. White noise is everywhere now, coming from fans in our electronics, air conditioners, heaters, and car engines. How would such noise affect the developing brain? Merzenich wondered.

To test this hypothesis, his group exposed rat pups to pulses of white noise throughout their critical period and found that the pups'
cortices were devastated.

"Every time you have a pulse," Merzenich says, "you are exciting everything in the auditory cortex—every neuron." So many neurons firing results in a massive BDNF release. And as his model predicted, this exposure brings the critical period to a premature close. The animals are left with undifferentiated brain maps and utterly indiscriminate neurons that get turned on by any frequency.

Merzenich found that these rat pups, like autistic children, were predisposed to epilepsy, and exposing them to normal speech caused them to have epileptic fits. (Human epileptics find that strobe lights at rock concerts set off their seizures. Strobes are pulsed emissions of white light and consist of many frequencies as well.) Merzenich now had his animal model for autism.

Recent brain scan studies now confirm that autistic children do indeed process sound in an abnormal way. Merzenich thinks that the undifferentiated cortex helps to explain why they have trouble learning, because a child with an undifferentiated cortex has a very difficult time paying attention. When asked to focus on one thing, these children experience booming, buzzing confusion—one reason autistic children often withdraw from the world and develop a shell. Merzenich thinks this same problem, in a milder form, may contribute to more common attention disorders.

Now the question for Merzenich was, could anything be done to normalize undifferentiated brain maps after the critical period? If he and his team could do so, they could offer hope for autistic children.

Using white noise, they first dedifferentiated the auditory maps of rats. Then, after the damage was done, they normalized and redifferentiated the maps using very simple tones, one at a time. With training, in fact, they brought the maps to an above-normal range. "And that," says Merzenich, "is exactly what we are trying to do in these autistic children." He is currently developing a modification of ForWord that is designed for autism, a refinement of the program that helped Lauralee.

What if it were possible to reopen critical-period plasticity, so that adults could pick up languages the way children do, just by being exposed to them? Merzenich had already shown that plasticity extends into adulthood, and that with work—by paying close attention—we can rewire our brains. But now he was asking, could the critical period of effortless learning be extended?

Learning in the critical period is effortless because during that period the nucleus basalis is always on. So Merzenich and his young colleague Michael Kilgard set up an experiment in which they artificially turned on the nucleus basalis in adult rats and gave them learning tasks where they wouldn't have to pay attention and wouldn't
receive a reward for learning.

They inserted microelectrodes into the nucleus basalis and used an electric current to keep it turned on. Then they exposed the rats to a 9 Hz sound frequency to see if they could effortlessly develop a brain map location for it, the way pups do during the critical period. After a week Kilgard and Merzenich found they could massively expand the brain map for that particular sound frequency. They had found an artificial way to reopen the critical period in adults.

They then used the same technique to get the brain to speed up its processing time. Normally an adult rat's auditory neurons can only respond to tones at a maximum of 12 pulses per second. By stimulating the nucleus basalis, it was possible to "educate" the neurons to respond to ever more rapid inputs.

This work opens up the possibility of high-speed learning later in life. The nucleus basalis could be turned on by an electrode, by microinjections of certain chemicals, or by drugs. It is hard to imagine that people will not—for better or for worse—be drawn to a technology that would make it relatively effortless to master the facts of science, history, or a profession, merely by being exposed to them briefly. Imagine immigrants coming to a new country, now able to pick up their new language, with ease and without an accent, in a matter of months. Imagine how the lives of older people who have been laid off from a job might be transformed, if they were able to learn a new skill with the alacrity they had in early childhood. Such techniques would no doubt be used by high school and university students in their studies and in competitive entrance exams. (Already many students who do not have attention deficit disorder use stimulants to study.) Of course, such aggressive interventions might have unanticipated, adverse effects on the brain—not to mention our ability to discipline ourselves—but they would likely be pioneered in cases of dire medical need, where people are willing to take the risk. Turning on the nucleus basalis might help brain-injured patients, so many of whom cannot relearn the lost functions of reading, writing, speaking, or walking because they can't pay close enough attention.

Merzenich has started a new company, Posit Science, devoted to helping people preserve the plasticity of their brains as they age and extend their mental lifespans. He's sixty-one but is not reluctant about calling himself old. "I love old people. I've always loved old
people. Probably my favorite person was my paternal grandfather, one of the three or four most intelligent and interesting people I've met in life." Grandpa Merzenich came from Germany at nine on one of the last clipper ships. He was self-educated, an architect and a building contractor. He lived to be seventy-nine, at a time when life expectancy was closer to forty.

"It's estimated that by the time someone who is sixty-five now dies, the life expectancy will be in the late eighties. Well, when you are eighty-five, there is a forty-seven percent chance that you will have Alzheimer's disease." He laughs. "So we've created this bizarre situation in which we are keeping people alive long enough so that on the average, half of them get the black rock before they die. We've got to do something about the mental lifespan, to extend it out and into the body's lifespan."

Merzenich thinks our neglect of intensive learning as we age leads the systems in the brain that modulate, regulate, and control plasticity to waste away. In response he has developed brain exercises for age-related cognitive decline—the common decline of memory, thinking, and processing speed.

Merzenich's way of attacking mental decline is at odds with mainstream neuroscience. Tens of thousands of papers, written about the physical and chemical changes that occur in the aging brain, describe processes that occur as neurons die. There are many drugs on the market and scores of drugs in the pipeline designed to block these processes and raise levels of falling chemicals in the brain. Yet,

Merzenich believes that such drugs, worth billions in sales, provide only about four to six months of improvement.

"And there is something really wrong about all this," he says. "It all neglects the role of what is required to sustain normal skills and abilities... It is as if your skills and abilities, acquired in the brain at some young age, are just destined to deteriorate as the physical brain deteriorates." The mainstream approach, he argues, is based on no real understanding of what it takes to develop a new skill in the brain, never mind to sustain it. "It is imagined" he says, "that if you manipulate the levels of the right neurotransmitter ... that memory will be recovered, and cognition will be useful, and that you will start moving like a gazelle again."
The mainstream approach doesn't take into account what is required to maintain a sharp memory. A major reason memory loss occurs as we age is that we have trouble registering new events in our nervous systems, because processing speed slows down, so that the accuracy, strength, and sharpness with which we perceive declines. If you can't register something clearly, you won't be able to remember it well.

Take one of the most common problems of aging, trouble finding words. Merzenich thinks this problem often occurs because of the gradual neglect and atrophy of the brain's attentional system and nucleus basalis, which have to be engaged for plastic change to occur. This atrophy leads to our representing oral speech with "fuzzy engrams," meaning that the representation of sounds or words is not sharp because the neurons that encode these fuzzy engrams are not firing in the coordinated, quick way needed to send a powerful sharp signal. Because the neurons that represent speech pass on fuzzy signals to all the neurons downstream from them ("muddy in, muddy out") we also have trouble remembering, finding, and using words. It is similar to the problem we saw occurring in the brains of language-impaired children, who also have "noisy brains."

When our brains are "noisy," the signal for a new memory can't compete against the background electrical activity of the brain, causing a "signal-noise problem."

Merzenich says the system gets noisier for two reasons. First because as everyone knows, "everything is progressively going to hell." But "the main reason it is getting noisier is that it is not being appropriately exercised." The nucleus basalis, which works by secreting acetylcholine—which, as we said, helps the brain "tune in" and form sharp memories—has been totally neglected. In a person with mild cognitive impairment the acetylcholine produced in the nucleus basalis is not even measurable.

"We have an intense period of learning in childhood. Every day is a day of new stuff. And then, in our early employment, we are intensely engaged in learning and acquiring new skills and abilities. And more and more as we progress in life we are operating as users of mastered skills and abilities."

Psychologically, middle age is often an appealing time because, all else being equal, it can be a relatively placid period compared with what has come before. Our bodies aren't changing as they did in adolescence; we're more likely to have a solid sense of who we are and be skilled at a career. We still regard ourselves as active, but we have a tendency to deceive ourselves into thinking that we are learning as we were before. We rarely engage in tasks in which we must focus our attention as closely as we did when we were younger, trying to learn a new vocabulary or master new skills. Such activities as reading the newspaper, practicing a profession of many years, and speaking our own language are
mostly the replay of mastered skills, not learning. By the time we hit our seventies, we may not have systematically engaged the systems in the brain that regulate plasticity for fifty years.

That's why learning a new language in old age is so good for improving and maintaining the memory generally. Because it requires intense focus, studying a new language turns on the control system for plasticity and keeps it in good shape for laying down sharp memories of all kinds. No doubt Fast ForWord is responsible for so many general improvements in thinking, in part because it stimulates the control system for plasticity to keep up its production of acetylcholine and dopamine. Anything that requires highly focused attention will help that system—learning new physical activities that require concentration, solving challenging puzzles, or making a career change that requires that you master new skills and material. Merzenich himself is an advocate of learning a new language in old age. "You will gradually sharpen everything up again, and that will be very highly beneficial to you."

The same applies to mobility. Just doing the dances you learned years ago won't help your brain's motor cortex stay in shape. To keep the mind alive requires learning something truly new with intense focus. That is what will allow you to both lay down new memories and have a system that can easily access and preserve the older ones.

The thirty-six scientists at Posit Science are working on five areas that tend to fall apart as we age. The key in developing exercises is to give the brain the right stimuli, in the right order, with the right timing to drive plastic change. Part of the scientific challenge is to find the most efficient way to train the brain, by finding mental functions to train that apply to real life.

Merzenich told me, "Everything that you can see happen in a young brain can happen in an older brain." The only requirement is that the person must have enough of a reward, or punishment, to keep paying attention through what might otherwise be a boring training session. If so, he says, "the changes can be every bit as great as the changes in a newborn."

Posit Science has exercises for memory of words and language, using Fast ForWord-like listening exercises and computer games for auditory memory designed for adults. Instead of giving people with fading memories lists of words to memorize, as many self-help books recommend, these exercises rebuild the brain's basic ability to process sound, by getting people to listen to slowed, refined speech sounds. Merzenich doesn't believe you can improve a fading memory by asking people to do what they can't. "We don't want to kick a dead horse with training," he says. Adults do exercises that refine their ability to
hear in a way they haven't since they were in the crib trying to separate out Mother's voice from background noise. The exercises increase processing speed and make basic signals stronger, sharper, and more accurate, while stimulating the brain to produce the dopamine and acetylcholine.

Various universities are now testing the memory exercises, using standardized tests of memory, and Posit Science has published its first control study in the *Proceedings of the National Academy of Sciences, USA*. Adults between the ages of sixty and eighty-seven trained on the auditory memory program an hour a day, five days a week, for eight to ten weeks—a total of forty to fifty hours of exercises. Before the training, the subjects functioned on average like typical seventy-year-olds on standard memory tests. After, they functioned like people in the broad forty-to-sixty-year-old range. Thus, many turned back their memory clock ten or more years, and some individuals turned it back about twenty-five years. These improvements held at a three-month follow-up. A group at the University of California at Berkeley, led by William Jagust, did "before" and "after" PET (positron emission tomography) scans of people who underwent the training, and found that their brains did not show the signs of "metabolic decline"—neurons gradually becoming less active—typically seen in people of their age. The study also compared seventy-one-year-old subjects who used the auditory memory program with those of the same age who spent the same amount of time reading newspapers, listening to audiobooks, or playing computer games. Those who didn't use the program showed signs of continuing metabolic decline in their frontal lobes, while those who used it didn't. Rather, program users showed increased metabolic activity in their right parietal lobes and in a number of other brain areas, which correlated with their better performance on memory and attention tests. These studies show that brain exercises not only slow age-related cognitive decline but can lead to improved functioning. And keep in mind that these changes were seen with only forty to fifty hours of brain exercise; it may be that with more work, greater change is possible.

Merzenich says they have been able to turn back the clock on people's cognitive functioning so that their memories, problem-solving abilities, and language skills are more youthful again. "We've driven people to abilities that apply to a much more youthful person—twenty or thirty years of reversal. An eighty-year-old is acting, operationally, like they are fifty or sixty years old." These exercises are now available in thirty independent-living communities.
and for individuals through the Posit Science Web site.

Posit Science is also working on visual processing. As we age, we stop seeing clearly, not just because our eyes fail but because the vision processors in the brain weaken. The elderly are more easily distracted and more prone to lose control of their "visual attention." Posit Science is developing computer exercises to keep people on task and speed up visual processing by asking subjects to search for various objects on a computer screen.

There are exercises for the frontal lobes that support our "executive functions" such as focusing on goals, extracting themes from what we perceive, and making decisions. These exercises are also designed to help people categorize things, follow complex instructions, and strengthen associative memory, which helps put people, places, and things into context.

Posit Science is also working on fine motor control. As we age, many of us give up on tasks such as drawing, knitting, playing musical instruments, or woodworking because we can't control the fine movements in our hands. These exercises, now being developed, will make fading hand maps in the brain more precise.

Finally, they are working on "gross motor control," a function that declines as we age, leading to loss of balance, the tendency to fall, and difficulties with mobility. Aside from the failure of vestibular processing, this decline is caused by the decrease in sensory feedback from our feet. According to Merzenich, shoes, worn for decades, limit the sensory feedback from our feet to our brain. If we went barefoot, our brains would receive many different kinds of input as we went over uneven surfaces. Shoes are a relatively flat platform that spreads out the stimuli, and the surfaces we walk on are increasingly artificial and perfectly flat. This leads us to dedifferentiate the maps for the soles of our feet and limit how touch guides our foot control. Then we may start to use canes, walkers, or crutches or rely on other senses to steady ourselves. By resorting to these compensations instead of exercising our failing brain systems, we hasten their decline.

As we age, we want to look down at our feet while walking down stairs or on slightly challenging terrain, because we're not getting much information from our feet. As Merzenich escorted his mother-in-law down the stairs of the villa, he urged her to stop looking down and start feeling her way, so that she would maintain, and develop, the sensory map for her foot, rather than letting it waste away.

Having devoted years to enlarging brain maps, Merzenich now believes there are times you want to shrink them. He has been working on developing a mental eraser that can eliminate a problematic brain map. This technique could be of great use for people who have post-traumatic
flashbacks, recurring obsessional thoughts, phobias, or problematic mental associations. Of course, its potential for abuse is chilling.

Merzenich continues to challenge the view that we are stuck with the brain we have at birth. The Merzenich brain is structured by its constant collaboration with the world, and it is not only the parts of the brain most exposed to the world, such as our senses, that are shaped by experience. Plastic change, caused by our experience, travels deep into the brain and ultimately even into our genes, molding them as well—a topic to which we shall return.

This Mediterranean-style villa where he spends so much time sits among low mountains. He has just planted his own vineyard, and we walk through it. At night we talk about his early years studying philosophy, while four generations of his spirited family tease each other, breaking into peals of laughter. On the couch sits Merzenich's latest grandchild, just a few months old and in the midst of many critical periods. She makes everyone around her happy because she is such a good audience. You can coo at her, and she listens, thrilled. You tickle her toes, and she is completely attentive. As she looks around the room she takes in everything.

4

Acquiring Tastes and Loves

What Neuroplasticity Teaches Us About Sexual Attraction and Love

A. was a single, handsome young man who came to me because he was depressed. He had just gotten involved with a beautiful woman who had a boyfriend, and she had begun to encourage him to abuse her. She tried to draw A. into acting out sexual fantasies in which she dressed up as a prostitute, and he was to "take charge" of her and become violent in some way. When A. began to feel an alarming wish to oblige her, he got very upset, broke it off, and sought treatment. He had a history of involvement with women who were already attached to other men and emotionally out of control. His girlfriends had either been demanding and possessive or castratingly cruel. Yet these were the women who thrilled him.
"Nice" girls, thoughtful, kind women, bored him, and he felt that any woman who fell in love with him in a tender, uncomplicated way was defective.

His own mother was a severe alcoholic, frequently needy, seductive, and given to emotional storms and violent rages throughout his childhood. A. recalled her banging his sister's head against the radiator and burning his stepbrother's fingers as a punishment for playing with matches. She was frequently depressed, often threatening suicide, and his role was to be on the alert, calm her, and prevent her.

His relationship with her was also highly serialized. She wore see-through nighties and talked to him as though he were a lover. He thought he recalled her inviting him into her bed when he was a child and had an image of himself sitting with his foot in her vagina while she masturbated. He had an exciting but furtive feeling about the scene. On the rare occasions when his father, who had retreated from his wife, was home, A. recalled himself as "perpetually short of breath," and trying to stop fights between his parents, who eventually divorced.

A. spent much of his childhood stifling his rage at both parents and often felt like a volcano about to burst. Intimate relationships seemed like forms of violence, in which others threatened to eat him alive, and yet by the time he had passed through childhood, it was for women who promised to do just that, and them alone, that he had acquired an erotic taste.

Human beings exhibit an extraordinary degree of sexual plasticity compared with other creatures. We vary in what we like to do with our partners in a sexual act. We vary where in our bodies we experience sexual excitement and satisfaction. But most of all we vary in whom or what we are attracted to. People often say they find a particular "type" attractive, or a "turn-on," and these types vary immensely from person to person.

For some, the types change as they go through different periods and have new experiences. One homosexual man had successive relations with men from one race or ethnic group, then with those from another, and in each period he could be attracted only to men in the group that was currently "hot." After one period was over, he could never be attracted to a man from the old group again. He acquired a taste for these "types" in quick succession and seemed more smitten by the person's category or type (i.e., "Asians" or "African-Americans") than by the individual. The plasticity of this man's sexual taste exaggerates a general truth: that the human libido is not a hardwired, invariable biological urge but can be curiously fickle, easily altered by our psychology and the history of our sexual encounters. And our libido can also be finicky. Much scientific writing implies otherwise and depicts the sexual instinct as a biological imperative, an ever-hungry brute, always demanding satisfaction—a glutton, not a gourmet. But human beings are more like gourmets and are drawn to types and have strong preferences; having
a "type" causes us to defer satisfaction until we find what we are looking for, because attraction to a type is restrictive: the person who is "really turned on by blondes" may tacitly rule out brunettes and redheads.

Even sexual preference can occasionally change. Though some scientists increasingly emphasize the inborn basis of our sexual preferences, it is also true that some people have heterosexual attractions for part of their lives—with no history of bisexuality—and then "add on" a homosexual attraction and vice versa.

Sexual plasticity may seem to have reached its height in those who have had many different partners, learning to adapt to each new lover; but think of the plasticity required of the aging married couple with a good sex life. They looked very different in their twenties, when they met, than they do in their sixties, yet their libidos adjust, so they remain attracted.

But sexual plasticity goes further still. Fetishists desire inanimate objects. The male fetishist can be more excited by a high-heeled shoe with a fur trim, or by a woman's lingerie, than by a real woman. Since ancient times some human beings in rural areas have had intercourse with animals. Some people seem to be attracted not so much to people as to complex sexual scripts, where partners play roles, involving various perversions, combining sadism, masochism, voyeurism, and exhibitionism. When they place an ad in the personals, the description of what they are looking for in a lover often sounds more like a job description than like that of a person they would like to know.

Given that sexuality is an instinct, and instinct is traditionally defined as a hereditary behavior unique to a species, varying little from one member to the next, the variety of our sexual tastes is curious. Instincts generally resist change and are thought to have a clear, non-negotiable, hardwired purpose, such as survival. Yet the human sexual "instinct" seems to have broken free of its core purpose, reproduction, and varies to a bewildering extent, as it does not in other animals, in which the sexual instinct seems to behave itself and act like an instinct. No other instinct can so satisfy without accomplishing its biological purpose, and no other instinct is so disconnected from its purpose. Anthropologists have shown that for a long time humanity did not know that sexual intercourse was required for reproduction. This "fact of life" had to be learned by our ancestors, just as children must learn it today. This detachment from its primary purpose is perhaps the ultimate sign of sexual plasticity.

Love too is remarkably flexible, and its expression has changed through history. Though we speak of romantic love as the most natural of sentiments, in fact the concentration of
our adult hopes for intimacy, tenderness, and lust in one person until death do us part is not common to all societies and has only recently become widespread in our own. For millennia most marriages were arranged by parents for practical reasons. Certainly, there are unforgettable stories of romantic love linked to marriage in the Bible, as in the Song of Songs, and linked to disaster in medieval troubadour poetry and, later, in Shakespeare. But romantic love began to gain social approval in the aristocracies and courts of Europe only in the twelfth century—originally between an unmarried man and a married woman, either adulterous or unconsummated, usually ending badly. Only with the spread of democratic ideals of individualism did the idea that lovers ought to be able to choose spouses for themselves take firmer hold and gradually begin to seem completely natural and inalienable.

It is reasonable to ask whether our sexual plasticity is related to neuroplasticity. Research has shown that neuroplasticity is neither ghettoized within certain departments in the brain nor confined to the sensory, motor, and cognitive processing areas we have already explored. The brain structure that regulates instinctive behaviors, including sex, called the hypothalamus, is plastic, as is the amygdala, the structure that processes emotion and anxiety. While some parts of the brain, such as the cortex, may have more plastic potential because there are more neurons and connections to be altered, even noncortical areas display plasticity. It is a property of all brain tissue. Plasticity exists in the hippocampus (the area that turns our memories from short-term to long-term ones) as well as in areas that control our breathing, process primitive sensation, and process pain. It exists in the spinal cord—as scientists have shown; actor Christopher Reeve, who suffered a severe spinal injury, demonstrated such plasticity, when he was able, through relentless exercise, to recover some feeling and mobility seven years after his accident. 'Merzenich puts it this way: "You cannot have plasticity in isolation ... it's an absolute impossibility." His experiments have shown that if one brain system changes, those systems connected to it change as well. The same "plastic rules"—use it or lose it, or neurons that fire together wire together—apply throughout. Different areas of the brain wouldn't be able to function together if that weren't the case.

Do the same plastic rules that apply to brain maps in the sensory, motor, and language cortices apply to more complex maps, such as those that represent our relationships, sexual or otherwise? Merzenich has also shown that complex brain maps are governed by the same plastic principles as simpler maps. Animals exposed to a simple tone will develop a single brain map region to process it. Animals exposed to a complex pattern, such as a melody of six tones, will not simply link together six different map
regions but will develop a region that encodes the entire melody. These more complex melody maps obey the same plastic principles as maps for single tones.

"The sexual instincts," wrote Freud, "are noticeable to us for their plasticity, their capacity for altering their aims." Freud was not the first to argue that sexuality was plastic—Plato, in his dialogue on love, argued that human Eros took many forms—but Freud laid the foundations for a neuroscientific understanding of sexual and romantic plasticity.

One of his most important contributions was his discovery of critical periods for sexual plasticity. Freud argued that an adult's ability to love intimately and sexually unfolds in stages, beginning in the infant's first passionate attachments to its parents. He learned from his patients, and from observing children, that early childhood, not puberty, was the first critical period for sexuality and intimacy, and that children are capable of passionate, protosexual feelings—crushes, loving feelings, and in some cases even sexual excitement, as A. was. Freud discovered that the sexual abuse of children is harmful because it influences the critical period of sexuality in childhood, shaping our later attachments and thoughts about sex. Children are needy and typically develop passionate attachments to their parents. If the parent is warm, gentle, and reliable, the child will frequently develop a taste for that kind of relationship later on; if the parent is disengaged, cool, distant, self-involved, angry, ambivalent, or erratic, the child may seek out an adult mate who has similar tendencies. There are exceptions, but a significant body of research now confirms Freud's basic insight that early patterns of relating and attaching to others, if problematic, can get "wired" into our brains in childhood and repeated in adulthood. Many aspects of the sexual script that A. played out when he first came to see me were repetitions of his traumatic childhood situation, thinly disguised—such as his being attracted to an unstable woman who crossed normal sexual boundaries in furtive relationships, where hostility and sexual excitement were merged, while the woman's official partner was cuckolded and threatening to reenter the scene.

The idea of the critical period was formulated around the time Freud started writing about sex and love, by embryologists who observed that in the embryo the nervous system develops in stages, and that if these stages are disturbed, the animal or person will be harmed, often catastrophically, for life. Though Freud didn't use the term, what he said about the early stages of sexual development conforms to what we know about critical periods. They are brief windows of time when new brain systems and maps develop with the help of stimulation from the people in one's environment.

Traces of childhood sentiments in adult love and sexuality are detectable in everyday behaviors. When adults in our culture have tender foreplay, or express their most intimate adoration, they often call each other "baby" or "babe." They use terms of endearment that their mothers used with them as children, such as "honey" and "sweetie pie," terms that evoke the earliest months of life when the mother expressed her love by feeding, caressing, and talking sweetly to her baby—what Freud called the oral phase, the first
critical period of sexuality, the essence of which is summed up in the words "nurtur-ance" and "nourish"—tenderly caring for, loving, and feeding. The baby feels merged with the mother, and its trust of others develops as the baby is held and nurtured with a sugary food, milk. Being loved, cared for, and fed are mentally associated in the mind and wired together in the brain in our first formative experience after birth. When adults talk baby talk, using words such as "sweetie pie" and "baby" to address each other, and give their conversation an oral flavor, they are, according to Freud, "regressing," moving from mature mental states of relating to earlier phases of life. In terms of plasticity, such regression, I believe, involves unmasking old neuronal pathways that then trigger all the associations of that earlier phase. Regression can be pleasant and harmless, as in adult foreplay, or it can be problematic, as when infantile aggressive pathways are unmasked and an adult has a temper tantrum. Even "talking dirty" shows traces of infantile sexual stages. After all, why should sex be thought "dirty" at all? This attitude reflects a child’s view of sex from a stage when it is conscious of toilet training, urination, and defecation and is surprised to learn that the genitals, which are involved in urination, and so close to the anus, are also involved in sex, and that Mommy permits Daddy to insert his "dirty" organ in a hole that is very close to her bottom. Adults are not generally bothered by this, because in adolescence they have gone through another critical period of sexual plasticity in which their brains reorganized again, so that the pleasure of sex becomes intense enough to override any disgust. Freud showed that many sexual mysteries can be understood as critical-period fixations. After Freud, we are no longer surprised that the girl whose father left her as a child pursues unavailable men old enough to be her father, or that people raised by ice-queen mothers often seek such people out as partners, sometimes becoming "icy" themselves, because, never having experienced empathy in the critical period, a whole part of their brains failed to develop. And many perversions can be explained in terms of plasticity and the persistence of childhood conflicts. But the main point is that in our critical periods we can acquire sexual and romantic tastes and inclinations that get wired into our brains and can have a powerful impact for the rest of our lives. And the fact that we can acquire different sexual tastes contributes to the tremendous sexual variation between us.