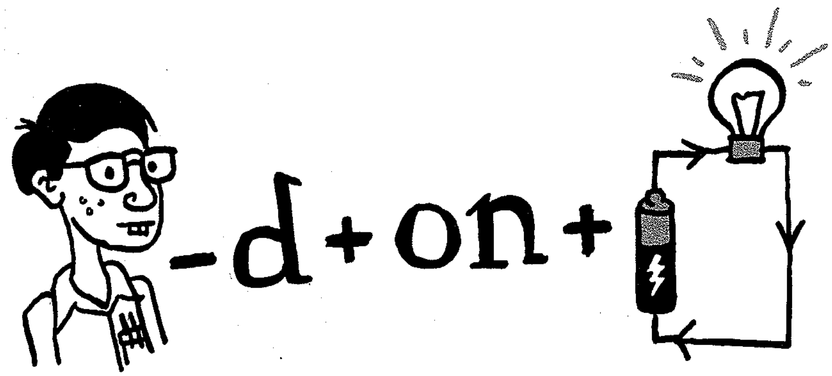
brain's thinking in unpredictable ways. That Spitzka intuited all this in 1901 is remarkable. And we can do even better today, since we know so much more about how neurons can affect global thinking patterns. We simply need to expand our scope and explore how individual neurons wire themselves together into circuits, which provide the raw material for our thoughts.

CHAPTER THREE

Wiring and Rewiring

We've seen how individual neurons work. But neurons often work best within larger and more sophisticated units called circuits—ensembles of neurons wired together for a common purpose.



It was probably the most traveled outfit in history. A starched white shirt, a white cravat. Off-white button-up breeches. A deep-blue frock coat with brass buttons. An incongruous straw hat with a floppy brim. And most important, a metal-tipped hickory cane—the famous cane with which Lieutenant James Holman clicked his way through Siberia, Mongolia, Jerusalem, Mauritius, China, South Africa, Tasmania, Transylvania, and seemingly everywhere else in the known world.

Holman joined Britain's Royal Navy at age twelve, in 1798, and stayed active until just before the War of 1812, when he caught a mysterious illness off the coast of North America. Naval doctors, stumped by his roaming joint pain and headaches, diagnosed "flying gout," a meaningless catchall syndrome. However fictitious, flying gout handicapped Holman and forced him out of the navy at twenty-five.

While adjusting to his new, sedentary life in England, he earned an appointment as a Naval Knight of Windsor—which sounded grand, but in reality meant drear and tedium. His only duty was attending chapel twice a day and saying extra prayers for the king, his lords, and various toadies around Windsor Castle. The rest of the time he sat around his small apartment, alone, and did nothing; he couldn't even read. Holman found life at Windsor such an existential torture that his physical health deteriorated, and a case of wanderlust gripped him. He soon fled England and spent much of the rest of his life roaming, plunging headlong into odd and often dangerous corners of the globe.

For one early trip, he got it into his head to cross Siberia. Thanks to the atrocious, teeth-rattling ruts on the roads, he ended up walking much of the way—strolling alongside the cart, holding on to a rope. But before reaching the Pacific he got kidnapped by officials of the tsar and deported as a spy, since no one believed that anyone would travel Siberia for fun. On later trips he chased down slave traders;

mapped the Australian Outback; negotiated with headhunters; dodged forest fires; charged into war zones; and crossed the Indian Ocean on a ship carrying a cargo of sugar and champagne (it wasn't all hardship). He also climbed Mount Vesuvius in mideruption, a jaunt that nearly burned the soles off his shoes but proved to him that he could handle anything, despite his handicap. Along the way he earned a reputation as quite a ladies' man, and he did good enough scientific work (on the drifting of seeds among islands) to get elected to the Royal Society and cited by Charles Darwin. He rarely traveled in luxury—his pension amounted to just £84 yearly—and he stretched that further by packing his own meals (usually fruit, wine, and tongue, a cut-rate meat that didn't spoil) and by wearing his old naval uniform everywhere. Altogether Holman and his naval jacket, straw hat, and cane traveled 250,000 miles*—equivalent to ten trips around the equator or one trip to the moon, making him the most prolific traveler the world had ever known.

He returned to England as little as possible, and whenever he did find himself marooned at home, he took advantage of his downtime to write travel books. Eclectic and rambling, they might include soy sauce recipes on one page, advice for hunting kangaroos on the next, and he was constantly quoting the many poems he'd had to memorize. (He also included plenty of gossip about robberies, affairs, and local customs like sponge baths.) Before Holman even finished writing a book, though, that old desire to roam would well up inside him. Indeed, with his first book, published in 1822, he scurried to leave England almost before he'd finished the page proofs. The book became a bestseller, but by the time the London literati got hold of it and could flip to the frontispiece to see a portrait of this curious author, Holman was a thousand miles distant.

Holman couldn't have known it, but that frontispiece, while handsome overall, had one unsettling feature: his eyes, which seemed to look in different directions. Later portraits were even less flattering. In one book's frontispiece he looked drugged, with eyes unfocused. A

later oil portrait showed him with an unsightly Rip Van Winkle beard and, again, vacant white eyes. In another depiction Holman is shown with his hand draped over a blank white globe, as if embracing a giant, irisless eyeball. Portraying him with a globe devoid of all features seems baffling at first, since Holman had covered more of the earth's surface than anyone alive. In truth, the blankness was fitting. Holman, you see, was blind.

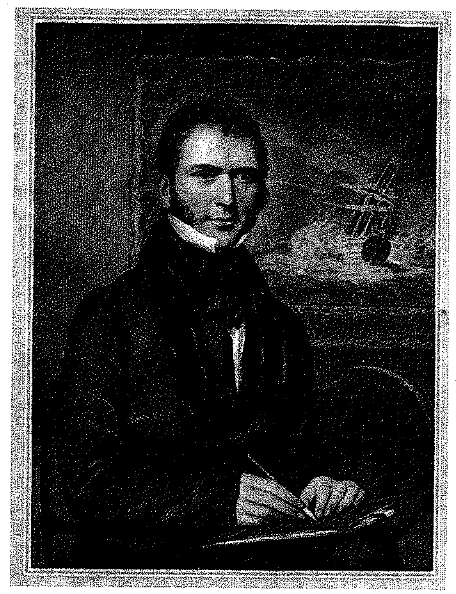
His health troubles had started in the navy. His ship's patrol route yo-yoed endlessly between Nova Scotia, where the wind practically froze icicles inside men's noses, and the Caribbean, where the sunlight beat down hot enough to melt candles. Something about those extremes ruined his joints, and his ankles grew so stiff and sore that he could no longer pull on his boots, much less negotiate the rolling decks. He took shore leave and recovered, but more bitter nor'easters and more wilting afternoons finally broke him. Soon his eyes began to ache something awful: mere sunlight felt like needles piercing his retinas. His world gradually fell dark, and even though his doctors treated his eyes with leeches, poultices, opium, and lead ointments, nothing could rescue his vision. Segments of his optic nerves* finally died when he was twenty-five, severing that connection to the brain and leaving him permanently sightless. He would eventually set foot in nearly every country on earth, but would set eyes on none of them.

Holman almost never got the chance to travel, thanks to his pseudo-ennoblement. Naval Knight bylaws said that he and his six fellow knights could not be absent from England more than ten days per year. Holman obeyed at first, but the monotony of life at Windsor proved unendurable, and after just a few months there his fevers returned and his flying gout began clawing at him again. He needed activity, stimulation, and his doctors begged the two wardens of the Naval Knights to let him catch the next ship out. The wardens, sympathetic at first, let Holman go, and the travel worked wonders. When he returned to Windsor, though, and the tedium descended, his aches and pains started to torment him anew. He got another travel visa and immediately felt better. But the illness started right up again after the next homecoming. And the next, and the next. Writing books allayed the pain a little—memory is a powerful analgesic—but each time he finished a manuscript he felt worse, and needed more leave to recover. After Holman missed some state funerals and coronations, the Windsor wardens began to grumble.

They weren't the only ones. After each book appeared, pundits would challenge the very idea that a blind man had, or even could have, traveled so widely. As we'll see, modern neuroscience lends credence to Holman, but in the early 1800s, society treated blind people pretty shabbily. Most blind folk simply scrounged up a bowl and started begging for farthings. The luckier ones (arguably) worked in traveling carnivals, where they were dressed up in donkey ears and/or huge fake eyeglasses and shoved onstage. There, they stumbled around without any real script; the entertainment lay in watching the production fall to shambles. Beggars and buffoons were what people thought of when they thought of the blind, not circumnavigation and adventure.

Even those who didn't dismiss Holman condescended to him. "I am constantly asked..." he once wrote, "what is the use of travelling to one who cannot see?" Some idiots questioned whether Holman had really left England, since all seven continents must look the same to him. Holman gritted his teeth and explained that foreign lands sounded different, smelled different, had different weather patterns and different daily rhythms. And in fact, Holman rarely neglected other senses in his writing. Timbers squeal and crockery gets smashed and ships pitch about seasickeningly in storms. Holman eats monkeys "cooked in the manner of an Irish stew" and describes touching everything from snakeskin to statues in the Vatican museum. You don't need two good eyes to describe the horrors of dysentery, or of swarms of flies and mosquitoes so thick that he needed chain mail to protect himself. And in some ways, Holman argued, his handicap made him a *superior* traveler:* instead of relying on a superficial view of a scene, his blindness forced him to talk to people and ask questions.

Still, Holman did have some practical tricks, tactics for navigating a world he couldn't see. Instead of indistinguishable paper bills, he demanded coins for currency. He acquired a special pocket watch whose hands he could trace without interfering with its ticking. To record his observations, he used an inkless dictation machine called a Noctograph,* a wooden slab with wires strung every half inch to guide his hand across the paper. And in exchange for free passage on ships, he often bartered his services—especially storytelling, like Homer of old—to relieve the tedium of ocean travel. One story he no doubt related involved a short excursion (1,400 miles) that he took with a friend—who happened to be deaf. "The circumstance was somewhat droll," he later wrote. "We were not infrequently exposed to a jest on the subject, which we generally participated in, and sometimes contributed to improve." All travelers need a sense of humor.



Blind explorer James Holman. Notice the unfocused eyes and Noctograph dictation machine.

Perhaps most important, James Holman succeeded in traveling the world by himself because he took advantage of neuroscience. Like most blind people, Holman explored his immediate environment with his hands. (For this reason women found Holman alluring—they adored his heightened sense of touch and often granted him permission to "look over" their faces and even bodies.) For navigating the world at large, however—for dodging poles and trees, for negotiating crowded bazaars—Holman relied not on his hands but on his hickory cane. He didn't use the cane the way blind people do today, as a sort of extended finger to feel his way along. His cane was too short, too heavy, too inflexible for that. Instead, he clicked the metal nib onto the pavement every few steps, and listened.

Whenever he clicked the cane, sound waves ricocheted off any nearby objects, and the echoes arrived back in each ear at slightly different times. After some practice, his brain learned to triangulate those time differences and determine the layout of the scene confronting him. The echoes also revealed details about an object's size, shape, and texture—hard, skinny statues sound different from soft, broad horses. Mastering this sensory capacity—called echolocation, the same sense that bats use—took years of determined work, but determination was James Holman's long suit. And once he'd perfected it, he could navigate everything from Vatican art galleries to Mount Vesuvius mideruption. Like flicks of a flashlight in a dark room, these cane clicks became Holman's sight.

Scientists often call the human brain the most elaborate machine that ever existed. It contains some hundred billion neurons, and the tip of an average axon wires itself up to thousands of neighbors, producing an inordinate number of connections for analyzing data. (There are so many connections that neurons seem to obey the famed "six degrees of separation" law: no two neurons are separated by more than six steps.) And cases like James Holman's reveal even more intricacies, since they show how the human brain can deviate from the standard wiring plan and sometimes even rewire itself, by changing

its wiring patterns over time. Some of these changes sound as fantastical as a blind man climbing volcanoes, but all of them give us insight into the incredible plasticity of our neural circuits.

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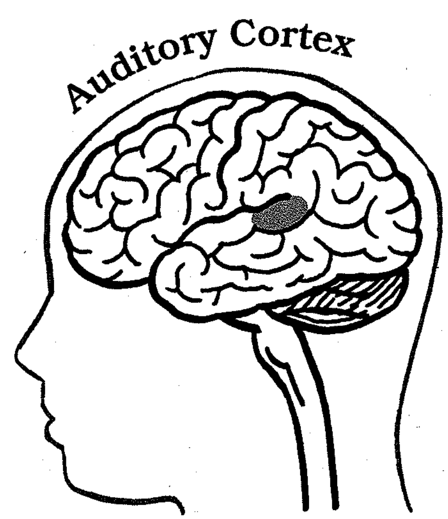
To see how brain circuits work, imagine a noise—like a *clack* on a cobblestone—arriving at James Holman's ear. The *clack* vibrates various bones and membranes inside his ear canal, and the sound wave eventually transfers its energy to a fluid in his inner ear. That fluid sloshes over rows of tiny hair cells and (depending on the sound) bends some of them to a greater or lesser extent. These hairs are connected to the dendrites of nearby nerve cells, which immediately fire and transmit electrical signals down their long axon "wires" toward the brain. Upon reaching the brain, the signal causes the axon to squirt a chemical soup into a nearby synapse. This finally arouses neurons in the auditory cortex, a patch of gray matter in the temporal lobe that analyzes the sound's pitch, volume, and rhythm.

Reaching the auditory cortex is only the start, though. For Holman to consciously recognize the *clack* or navigate with it, the signal has to circulate to other patches of gray matter for further processing.



And reaching those other patches of gray matter requires going subterranean—diving beneath the gray matter surface and into the brain's white matter.

White matter consists largely of high-speed axon cables that zip information from one gray matter node to another, at speeds up to 250 miles per hour. These axons can shuttle information around so quickly because they're fatter than normal axons, and because they're sheathed in a fatty substance called myelin. Myelin acts like rubber insulation on wires and prevents the signal from petering out: in whales, giraffes, and other stretched creatures, a sheathed neuron can send a signal multiple yards with little loss of fidelity. (In contrast, diseases that fray myelin, like multiple sclerosis, destroy communication between different nodes in the brain.) In sum, you can think about the gray matter as a patchwork of chips that analyze different types of information, and about the white matter as cables that transmit information between those chips.

(And before we go further, I should point out that "gray" and "white" are misnomers. Gray matter looks pinkish-tan inside a living skull, while white matter, which makes up the bulk of the brain, looks pale pink. The white and gray colors appear only after you soak the brain in preservatives. Preservatives also harden the brain, which is normally tapioca-soft. This explains why the brain you might have dissected in biology class way back when didn't disintegrate between your fingers.)

A message traveling through a white-matter cable can either stir other neurons to life (pay attention!) or anesthetize them (pay no attention!). But given the inordinate number of neurons we have, and given the bazillions of pathways that run between different patches of neurons, one key question in neuroscience is how the *clack* signal "knows" which path to follow, and which neighbors to excite and which to inhibit. The answer turns out to be fairly simple: like James Holman's cart through Siberia, brain signals follow ruts.

Start with two neurons. If one neuron causes another to fire in

quick succession over and over, the synapse between them actually changes in response. The axon tip of neuron one swells larger and starts packing in more bubbles of neurotransmitters to flood the synapse between them; wholly new axon branches might even sprout up. Neuron two can then make listening to neuron one a priority by extending more dendrite receptors back toward it. This allows neuron two to respond to even low-intensity prompts. Overall, just as a wagon wheel will carve a rut into the road after repeated journeys, repeated neuron firings will carve ruts into the brain that make signals much more likely to follow some neural tracks than others.

Scientists use a different metaphor to explain how neural connections grow stronger over time: *neurons that fire together wire together.* And usually it's not just two or three neurons firing and wiring together. Once a rut gets established, circuits of many thousands of neurons will fire in sequence.*

Thanks to white matter cables, these circuits can link together even distant patches of gray matter, allowing the brain to carry out complicated actions automatically. We're all born with circuits in our lower brain, for example, that control reflexes like sneezing, gagging, and yawning: as soon as the first neurons in the sequence fire, all the others follow, like a row of dominoes. That's why the steps involved in a sneeze or yawn rarely vary. Circuits in the higher brain work in the same way. After tons of practice, we all learned to link the letters d-o-g in our *Dick and Jane* primer with both an image of a fuzzy quadruped and with the sound *duh-aw-guh.* Eventually, any one of that triad automatically evokes the others. Negative experiences can wire neurons together, too. Enter an alley where you once had a fright, and its smells and shadows will reawaken your terror circuits.

All human brains subscribe to a standard wiring plan, which ensures that certain patches of neurons can always talk to certain other patches—and good thing. Your eyes better be able to rouse your fear circuits, and your fear circuits better be able to tell your legs to skedaddle, or you won't last long outdoors. This general wiring scheme gets laid down during our fetal days, when axons begin to bud and grow like shoots. That said, the general wiring diagram can vary in its details from person to person. One dramatic example of this is synesthesia, a condition in which people's senses blend together in trippy ways.

For most people, one sensory input produces just one sensory experience. Cherries simply taste like cherries, and rubbing sandpaper on the skin simply feels scratchy. For people with synesthesia, one sensory input leads to multiple outputs—the expected cherry taste, plus, say, a phantom tone. These superadded sensations are involuntary and consistent: each time the synesthete hears G-sharp, the exact same unaccountable pepper smell floods her nose. Synesthesia is idiosyncratic as well: while one person always sees the number 5 as fuchsia, another insists it's key-lime-pie green.

The most common type of synesthesia produces a symphony of color, especially when people hear certain sounds or see certain letters and numbers. Richard Feynman saw ecru *j*'s, indigo *n*'s, and chocolate *x*'s inside equations. Vladimir Nabokov once said that for him, the long vowel *aaah* has "the tint of weathered wood," while the shorter *ah* "evokes polished ebony." Franz Liszt used to berate his orchestra—who could only stare back, bewildered—for playing his music the wrong color: "Gentlemen, a little bluer, please, the tone depends on it!" Another time he implored: "That is a deep violet [passage]! . . . Not so rose."

Color-sound and color-letter synesthesia are the most common types because of brain geography: some of the regions that analyze sounds, letters, and colors lie right near each other, so signals can easily leak across the border. In theory, though, synesthesia can link any two sensations in the brain, and sixty known types exist. Hearing-motion synesthetes might hear a siren song emerging from a simple screen saver of moving dots. Touch-emotion synesthetes might feel silk as calming, oranges as shocking, wax as embarrassing, and denim as morose (so much for your favorite jeans). To touch-taste synes-

thetes, wrought-iron fences might taste salty, or certain kinds of meat "pointy." (One man pouted before a dinner party that the chicken he'd fricasseed came out too "spherical.") Sexual synesthetes might see colored shapes floating in front of them during coitus. Color-time synesthetes can experience days of the week, months of the year, or even stages of life as a patchwork of shades and hues. Imagine listening to Jacques's "seven ages of man" speech from *As You Like It*, and watching a rainbow envelop the stage.

Synesthesia probably has a genetic component, since it runs in families and pops up in most cultures. Importantly, too, neurologists have ruled out the idea that synesthetes are just talking metaphorical jive, the way the rest of us speak of "loud shirts" and "sharp cheddar." These people's brains actually work differently, as tests reveal. One experiment involved filling a piece of paper with a bunch of alarm-clock fives (5), but also scattering a few blocky twos (2) in there. Normal people find it nearly impossible to pick out the 2s without hunting one by one. To synesthetes, each 2 pops out in Technicolor, instantly. (It's similar to the way numbers pop out automatically on color-blind tests.) As another trick, if you show a synesthete, say, a giant numeral 4 made up of rows and rows of tiny 8s, the figure's color will flip depending on whether she focuses on the whole (the 4) or the pixels (the 8s). Other tests make synesthetes squirm. Normal people have no trouble reading text of basically any color. For synesthetes, numbers or letters that are the "wrong" color can disorient or repel them, since the colors on the page do battle with the colors in their minds.

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Neuroscientists know in a general way how synesthesia must work: the neuron circuits that process one sense must be accidentally strumming the circuits that process another sense, causing both sets to hum simultaneously. Determining exactly why that happens, though, has proved tricky. Two possible explanations have emerged, one anatomical, one functional. The anatomical theory blames poor pruning of neurons during childhood. All babies have far more neurons than they need; their neurons also have an excessive number of axon and dendrite branches. (As a result, young children probably experience synesthesia all the time.) As children develop, certain neurons begin firing together and wiring together, and those active neurons remain healthy. Meanwhile, unused neurons starve and die off. Excess branches get pruned back as well, like a maple near a power line. This destruction sounds brutal—neural Darwinism—but it leads to tighter, stronger, more efficient circuits among survivors. Perhaps the brains of synesthetes don't prune well. Perhaps their brains leave extra connections in place that link different sensory regions.

The functional theory suggests that neurons get pruned just fine, but that some neurons can't inhibit their neighbors very well. Again, our highly connected neurons have to discourage signals from shooting down stray paths to the wrong parts of the brain; they do so by skunking certain neighbors with inhibitory chemicals. But even if those stray paths lie dormant, they still exist—and could, in theory, open up and become active. Perhaps, then, the brains of synesthetes fail to inhibit these underground channels, and information leaks from one brain region to another.

The first clue for deciding between the functional and anatomical theories came from a Swiss chemist. In 1938 Albert Hofmann's drug company was searching for new stimulants, and he began investigating some chemicals derived from a fungus. He soon drifted to other compounds but had a nagging feeling that the fungi had more to teach him. So on a Friday afternoon in April 1943, he whipped up a fresh batch of one chemical, called lysergic acid diethylamide (in German, Lyserg-Säure-Diäthylamid). During the synthesis he suddenly felt woozy and saw streaks of color. He later guessed he'd gotten some powder on his finger, then rubbed his eyes. But he wasn't sure, so he tested his guess on Monday, April 19—forevermore known as Bicycle Day. He dissolved a tiny amount of powder, a quarter of a milligram, in a quarter shot of

water. It had no taste, and down the hatch it went. This happened at 4:20 p.m., and although Hofmann tried to record his sensations in his lab journal, by five o'clock his handwriting had deteriorated into a scrawl. His last words were "desire to laugh." Feeling unsettled, he asked his assistant to escort him home on his bicycle. It was quite a trip.

On the ride, the streaks of color reappeared before his eyes, and everything became elongated and distorted, as if reflected in a curved mirror. Time slowed down as well: Hofmann thought the trip took ages, but the assistant remembered furious pedaling. In his drawing room at home, Hofmann struggled to form coherent sentences, but finally made it clear that (for some reason) he thought milk would cure him. A neighbor woman patiently hauled bottle after bottle to him, and he chugged two liters that night, to no avail. Worse, Hofmann began having supernatural visions. His mind transmogrified the neighbor into a witch, and he felt a demon rise up inside him and clutch his soul. Even his furniture seemed possessed, trembling with menace. He felt certain he'd die right there on his couch.

Only hours later did he calm down, and he actually enjoyed the last hour. His eyes became veritable kaleidoscopes, with *Fantasia*-like fountains of color "exploding [and] rearranging and hybridizing themselves in constant flux." It also pleased him, he later reported, that "every acoustic perception, such as the sound of a door handle or a passing automobile, became transformed into optical perceptions. Every sound generated a vividly changing image, with its own consistent form and color." In other words, the drug produced synesthesia, something he'd never experienced.

Hofmann's Lyserg-Säure-Diäthylamid eventually became known as LSD, and since then thousands of Phish and Grateful Dead fans have had similar experiences. Tripping on LSD obviously can't change the brain's hardwired circuits. LSD can interfere with neurotransmitters, however, and warp the information flowing through those circuits for a few hours. It's like flipping your television from a Ken Burns documentary to a David Lynch nightmare sequence—the same circuitry is providing the picture, but the content is much wilder. This provides strong support for the functional theory of synesthesia. There's some evidence that natural synesthetes still might have brains that are wired a little differently. But the experience of Hofmann and others suggests that we all might have a talent for synesthesia latent inside us, if only we could tap it.

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Hofmann's drug-induced synesthesia showed that certain experiences can alter the flow of information through our neuronal wires, at least temporarily. But can any experiences actually *rewire* brain circuits in a permanent way?

Children's brains can remodel themselves quite easily and form all sorts of new connections: that's how they sponge up language and so much else. For most of the past century, though, neuroscientists considered remodeling in the adult brain impossible, thanks in part to Santiago Ramón y Cajal. Cajal spent a decade injuring the nerves and neurons of animals to test how well those tissues recovered. He found that peripheral nerves could often regenerate themselves (which explains why surgeons can reattach severed hands, feet, and penises, and get them working again). But neurons in the adult brain never grew back. This led Cajal to make the bleak declaration that "in the adult brain, nervous pathways are fixed and immutable. Everything may die, nothing may be regenerated."

Other observations supported Cajal's pessimism. Compared to children, adults have a much tougher time learning new skills like languages, a sign of neural sclerosis. And if adults suffer strokes or other brain damage, they might lose certain skills permanently, since neurons never grow back. Moreover, the lack of adult plasticity made sense from an evolutionary perspective. If the adult brain changed too easily, the thinking went, circuits controlling important behaviors and memories would unravel, and skills would evaporate from our

minds. As one scientist observed, a fully plastic brain "learns everything and remembers nothing."

All that's true. But neuroscientists were a little hasty in declaring that the soft, pliable clay of the infant brain always gives way to sturdy but brittle ceramic. Even if the adult brain cannot grow new neurons* or repair damaged ones, that doesn't mean that all neuron *pathways* are fixed and immutable. With the right training, neurons can indeed change how they behave and transmit data. Old brain wires can learn astounding new tricks.

In the late 1960s, a degenerative eye disease claimed both retinas of a sixteen-year-old Wisconsinite named Roger Behm, rendering him blind. Forty years later he took a flier on a "vision substitution" device that a local scientist had built. The device consisted of a black-and-white video camera mounted on Behm's forehead, with a ribbon of wires leading down into his mouth. The wires ended in a rectangular green electrode, not much bigger than a postage stamp, that rested on Behm's tongue. The camera fed its images to this electrode, which transformed each pixel into a buzz of electricity reminiscent of seltzer bubbles: white pixels tingled his tongue a lot; black pixels gave no tingle; gray were intermediate. Behm was supposed to use the tongue "image" to interact with the world around him.

As you might expect, this flummoxed him at first. He nevertheless learned how to detect motion versus stillness rather quickly. He started picking out triangles, circles, and other Euclidians not long afterward. He graduated to common objects like cups, chairs, and telephones. Soon he could pick out logos on football helmets and sort playing cards by their suits, even navigate a simple obstacle course. Nor was Behm unique or special in picking up these skills. Other blind people learned how to use mirrors, pick out overlapping objects, or follow the writhing dance of a candle flame.

The man behind the device, Paul Bach-y-Rita, became a neuroscientist in a roundabout way. (Although a Bronx native, Bach-y-Rita had a compound Catalan surname, like Santiago Ramón y Cajal.) Bach-y-Rita attended medical school in Mexico City on a dare, then dropped out to work, among other itinerant jobs, as a masseur and a fisherman in Florida. He also taught anatomy to blind people who were studying to become masseurs, which helped him understand how they interacted with the world. (The blind, with their heightened sense of touch, make fine masseurs and masseuses.) Eventually he returned to medical school and started working with blind patients. But Bach-y-Rita really found his purpose in life after his father, Pedro, suffered a massive stroke in 1959 and was left half paralyzed and speechless.

Pedro entered a rehabilitation clinic, but when his progress plateaued, his doctors declared him doomed and suggested a nursing home, since his fixed and immutable brain would never recover. This fatalism—so common in rehab facilities then—angered Bach-y-Rita's brother, a doctor named George. So George designed his own rehab regimen. It sounded harsh: George made Pedro crawl like an infant at first, learning how to move each limb again, before gradually working him up to his feet. He then made Pedro do household chores such as sweeping the porch and scrubbing pots and pans. Pedro struggled mightily and appeared to make little progress, but the repetitive motions eventually retrained his brain: he not only regained the ability to talk and walk, he resumed his teaching job, remarried, and started hiking again. Pedro in fact died (seven years later, of a heart attack) while hiking in the mountains of Colombia, at age seventy-three. His autopsy revealed extensive lingering damage, especially to white matter cables that connect certain patches of gray matter to each other. Importantly, though, the gray matter itself still worked. And his brain proved plastic enough to reroute the cues for walking and talking around the ravaged tissue. That is, instead of routing signals from A to B, it now routed them from A to C and then C to B—not the most efficient path, but one that improved over time as the mental ruts grew deeper.

Inspired, Paul Bach-y-Rita did additional residencies in neurology

and rehab medicine, and decided to investigate brain plasticity himself, especially how blind people might regain a vestige of sight. His first "brain port" used a hand-cranked video camera; it projected an image onto the viewer's back via vibrating Teflon studs implanted in a dentist's chair. With just four hundred pixels, the images looked like a black-and-white television with poor focus. Nevertheless, with practice people could pick out individuals based on their hairstyles and faces, including 1960s supermodel Twiggy. (The patients shrugged when shown *Playboy* centerfolds, however—touch still beats sight in some areas.)

When microprocessors got small enough, Bach-y-Rita built devices to stimulate the tongue, one of the body's most sensitive tactile areas. (Saliva also makes the mouth more conductive than bare skin, lowering the necessary voltage.) And the devices really gained legitimacy when scientists started scanning the brains of patients while they used them. The scans revealed that, even though the video information came streaming in through the tongue, the brain's vision centers crackled with activity. Neurologically, this input was indistinguishable from "sight." Psychologically, too, the patient experienced the tactile tongue data as vision. Blind people using the devices perceived objects as being "out there" in space in front of them, not on their tongues. They flinched from balls flung at them, and could sense when objects moved closer or farther away because they grew larger or smaller. They even fell prey to certain optical illusions, like the "waterfall effect." If you stare at something in motion (like a waterfall) for several seconds and then look away, whatever you focus on next seems to move of its own accord. Bach-y-Rita's device induces this same vertiginous feeling in blind people, further proof of a latent neurological ability to see.

Meanwhile, Bach-y-Rita's team developed other sensory substitution devices. A leper who'd lost the sense of touch in his hands (leprosy destroys nerves) donned a special glove that piped tactile information to his forehead instead; within minutes he could feel the cracks on a table and distinguish between rough logs, smooth aluminum tubes, and soft rolls of toilet paper. Bach-y-Rita also worked on "electric condoms." Many paralyzed men can still get erections, even if they can't feel them, and Bach-y-Rita's device, if ever completed, would pipe electric orgasms into their brains.

Most dramatically, Bach-y-Rita's team has restored people's sense of balance. This work started with a thirty-nine-year-old Wisconsin woman named Cheryl Schiltz, who'd taken an antibiotic called gentamicin after a hysterectomy in 1997. Gentamicin fights infections well but has a nasty habit of destroying the tiny hairs in the inner ear that keep us balanced and upright. Although these hairs are located in different tubes than the hairs that help us hear, they work the same basic way. A gel inside the tubes sloshes back and forth like jiggled Jell-O as our heads tip this way and that. This causes the hairs embedded in the gel to bend to and fro and thereby trigger certain neurons. From this data the brain determines whether we're standing upright and then corrects for deviations. With those hairs destroyed, the balance center in Schiltz's brain (the vestibular nuclei) went on the fritz and started shooting out signals at random to her muscles, forcing her to sway side to side, with little jerks. Worse, she always felt on the verge of toppling over, even while she was lying down, like a permanent case of the drunken spinnies. Schiltz and other gentamicin victims call themselves Wobblers. Most can barely navigate their own homes much less brave the outside world, where a simple zigzag on a carpet can send them reeling. Not a few Wobblers commit suicide.

Although skeptical, Schiltz let Bach-y-Rita's team rig her up in a green construction helmet with a tiny balance and some electronics mounted inside. Like Behm's device, wires snaked down from the headpiece to an electrode in Schiltz's mouth. When standing tall and true, she felt a kazoo buzz on the center of her tongue. When her head drooped or swayed, she felt the buzz slide forward, backward, or sideways. Her goal was to shift her posture to keep the buzz in the center at all times. The buzz felt bizarre to her, but she got the hang of it

quickly. After sessions of just five minutes, she found she could stand on her own for a few precious seconds. One day she drilled for twenty straight minutes and found she could walk without staggering. Further practice improved her balance still more, and eventually Schiltz dispensed with the helmet altogether. She even learned to jump rope and ride a bike again.

More poignantly, she began training others on how to use the device, including Bach-y-Rita himself. After being diagnosed with cancer in 2004, Bach-y-Rita took a chemotherapy drug that damaged his own inner ear hairs and wiped out his sense of balance. So Schiltz walked him through how to use the green helmet—returning the favor to him, and ensuring that he would walk on his own right up until his death in 2006.

Scientists are still debating exactly how sensory substitution devices changed the brains of people like Behm and Schiltz. One good guess is that these devices, in rerouting information from the tongue to the vision and balance centers, take advantage of pathways and feedback loops that already exist. When eating an apple, for instance, your brain naturally combines information about its taste, crunch, and shiny red finish to give you a more comprehensive understanding. So we already mix some sensory input, and maybe the tongue data getting transformed into visual data is just an extreme example. In addition, as LSD synesthesia shows, there are plenty of dormant, underground, pseudo-synesthesic channels inside the brain to exploit as well.

It seems that our brains, being partly plastic, can swap one sense for another no matter how it gets piped in. This has profound implications for how we understand the senses in general. From this point of view, all the ears, eyes, and nostrils really do is tickle certain nerves. As a result, all sensory input looks pretty much the same after it leaves the sense organ and enters the nervous system: it's nothing but chemical and electrical blips. It's really our neuron circuits, not our sensory equipment, that decipher incoming signals and conjure up perceptions.

Scientists have by no means resolved all the scientific issues here, much less the philosophical conundrums. And frankly, the debates surrounding these devices can get pretty Jesuitical—*can blind people ever truly see?* But according to Bach-y-Rita, "We don't see with the eyes, we don't hear with the ears. All of that goes on in the brain." If that's true, then blind people really can learn to see, whether through their tongues, like Behm, or through their ears, like James Holman and his latter-day descendants.

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Bach-y-Rita exploited modern electronics to remodel people's brains, but in truth, we don't need anything so sophisticated to take advantage of neural plasticity. Echolocators can transform their brains with nothing more advanced than their own teeth, tongues, and lips.

The most famous living echolocator, Daniel Kish, lost both his eyes at thirteen months to retinoblastoma, eye cancer; his sockets are hollow scars. But at age two, all on his own, he discovered the power of echoes. He developed a way of click-click-clicking his tongue—like a gas stove, albeit slower—to shoot out exploratory sound waves. He now navigates by listening for the echoes that reverberate around him.

To see how this works, imagine Kish approaching an object while walking down the sidewalk. *Click-click-click.* He notices that his tongue clicks echo back from points near the ground, but that the echoes stop at about bellybutton height. A few steps on, the echoes bounce back up to chest height; a few more steps, and they drop again. That echo profile indicates a parked sedan. Similarly, telephone poles produce a tall and skinny profile. Sound quality also provides clues: whereas cars reflect noise sharply, bushes muffle it.

Kish can echolocate with enough agility to climb trees, dance, and ride his bike in heavy traffic. He also bought a twelve-by-twelve-foot cabin in Angeles National Forest, near his home, and then spent days alone there navigating trails and crossing streams on slippery rocks. Kish's abandon has gotten him injured at times—smashed teeth, a broken heel. He also woke up in his cabin one night to find it

on fire (bad chimney) and barely escaped. But he calls these frights "the price of freedom." As he has written, "Running into a pole is a drag, but never being allowed to run into a pole is a disaster."* It's a sentiment James Holman would have hear-heared.

As a matter of fact, the feats of modern echolocators like Kish lend credence to Holman's life story. On brain scans, echolocators show strong activity in the visual cortex while they're listening to clicks. That's probably because vision neurons, in helping us see things, also help us navigate the world around us. So they'd naturally be recruited for echolocation even if the raw input is auditory. After years of listening to the echoes from his cane, James Holman's brain almost certainly remodeled itself in the same way. His auditory neurons and vision neurons had fired together so frequently and wired themselves together so intimately that translating sound maps into spatial maps became instinctual.

Unfortunately, Holman had fewer and fewer opportunities to exercise that instinct over the years. His health depended on travel, but as he began to request more and more leave time from the Naval Knights and began to travel farther and farther afield, and especially as he began to profit on his travels by publishing books—books full of exploits, such as climbing Mount Vesuvius, that seemed possible only for an able-bodied man—the wardens started seething. In retrospect, Holman probably had a psychosomatic illness: the depression that plagued his mind during his idle time in England also afflicted his body; conversely, traveling buoyed his spirits and relieved his physical pain. But with every trip the wardens of Windsor became more convinced that Holman was scamming them, and they began to forbid his travel, essentially sentencing him to house arrest. During these spells Holman appealed for help to every medical and political authority he could—a young Queen Victoria even got involved. But like Pharaoh of old, the wardens hardened their hearts and would not listen.

By 1855 Holman, in his midsixties, could barely manage a holiday to France anymore. And in truth, poor health was just one of several painful realities he had to face. When abroad, he kept wearing that staple of his traveling days, his naval uniform. But the coat and breeches had gone so out of fashion that even other sailors barely recognized him as a former officer. Worse, Holman's celebrity with the general public had dimmed. He published his last travel book in 1832, and year by year he fell deeper into obscurity. On the rare occasions when a contemporary did mention him, it was usually in the past tense.

After turning seventy Holman stopped traveling altogether and rarely left his apartment. Friends worried about him, but it emerged that he'd actually thrown himself into one last journey, into his past, to write his autobiography. The long hours he spent straining on the Noctograph dictation machine depleted him further, but he pushed himself because he imagined the book would secure his legacy at last. He still wanted recognition that his journeys had meant something—and meant something beyond the fact that a blind man had undertaken them. He saw himself not as a sightless Marco Polo but as Marco Polo's equal.

He completed the autobiography just before dying, in 1857. Sadly, no publishing house would take it, citing poor sales of his previous work. He left it to a literary executor, but that man in turn soon died, and within a few decades the book was lost to history.

Almost everything we know about Holman's personal life, then, comes from his surviving books—and it's not much. His favorite memories, his greatest disappointments, the names of his lovers, all of that remains unknown. He never even revealed how he first learned to echolocate. In fact, his travelogues spend amazingly little time discussing his blindness. Only one passage stands out for its frank discussion of his handicap and how it changed his worldview. In it, Holman was reminiscing about a few rendezvous from his past. Disarmingly, he admitted that he had no idea what his paramours looked like, or even whether they were homely. Moreover, he didn't care: by abandoning the standards of the sighted world, he argued, he could

tap into a more divine and more authentic beauty. Hearing a woman's voice and feeling her caresses—and then filling in what was missing with his own fancy—gave him more pleasure than the mere sight of a woman ever had, he said, a pleasure beyond reality. "Are there any who imagine," Holman asked, "that my loss of eyesight must necessarily deny me the enjoyment of such contemplations? How much more do I pity the mental darkness which could give rise to such an error."

Holman was talking about love here; but in talking about desires and contemplations above and beyond what his eyes could strictly see, he was getting at something bigger—something bigger about himself, and about how all human beings perceive the world. With regard to sensory substitution, Paul Bach-y-Rita said, "We don't see with the eyes. We see with the brain." That sentiment is true in a broader sense as well. We all construct our reality to some degree, and if Holman augmented the scenes around him with his own imaginings, well, so do the rest of us. In other words, our neurons do more than simply record the world around us. As we'll see next chapter, neuron circuits actually wire themselves together into still larger units, allowing our brains to reinterpret and remake what we see—infusing simple sights with layers of meaning and coloring mere perceptions with our own desires.