Introduction

Because brain science is a fast-moving field, it's rare to step back to view the lay of the land, to work out what our studies mean for our lives, to discuss in a plain and simple way what it means to be a biological creature. This book sets out to do that.

Brain science matters. The strange computational material in our skulls is the perceptual machinery by which we navigate the world, the stuff from which decisions arise, the material from which imagination is forged. Our dreams and our waking lives emerge from its billions of zapping cells. A better understanding of the brain sheds light on what we take to be real in our personal relationships and what we take to be necessary in our social policy: how we fight, why we love, what we accept as true, how we should educate, how we can craft better social policy, and how to design our bodies for the centuries to come. In the brain's microscopically small circuitry is etched the history and future of our species.

Given the brain's centrality to our lives, I used to wonder why our society so rarely talks about it, preferring instead to fill our airwaves with celebrity gossip and reality shows. But I now think this lack of attention to the brain can be taken not as a shortcoming, but as a clue: we're so trapped inside our reality that it is inordinately difficult to realize we're trapped inside anything. At first blush, it seems that perhaps there's nothing to talk about. Of course colors exist in the outside world. Of course my memory is like a video camera. Of course I know the real reasons for my beliefs.

The pages of this book will put all our assumptions under the spotlight. In writing it, I wanted to get away from a textbook model in favor of illuminating a deeper level of enquiry: how we decide, how we perceive reality, who we are, how our lives are steered, why we need other people, and where we're heading as a species that's just beginning to grab its own reins. This project attempts to bridge the gap between the academic literature and the lives we lead as brain owners. The approach I take here diverges from the academic journal articles I write, and even from my other neuroscience books. This project is meant for a different kind of audience. It doesn't presuppose any specialized knowledge, only curiosity and an appetite for self-exploration.

So strap in for a whistle-stop tour into the inner cosmos. In the infinitely dense tangle of billions of brain cells and their trillions of connections, I hope you'll be able to squint and make out something that you might not have expected to see in there. You.

1

WHO AM I?

All the experiences in your life – from single conversations to your broader culture – shape the microscopic details of your brain. Neurally speaking, who you are depends on where you've been. Your brain is a relentless shape-shifter, constantly rewriting its own circuitry – and because your experiences are unique, so are the vast, detailed patterns in your neural networks. Because they continue to change your whole life, your identity is a moving target; it never reaches an endpoint.

Although neuroscience is my daily routine, I'm still in awe every time I hold a human brain. After you take into account its substantial weight (an adult brain weighs in at three pounds), its strange consistency (like firm jelly), and its wrinkled appearance (deep valleys carving a puffy landscape) – what's striking is the brain's sheer physicality: this hunk of unremarkable stuff seems so at odds with the mental processes it creates.

Our thoughts and our dreams, our memories and experiences all arise from this strange neural material. Who we are is found within its intricate firing patterns of electrochemical pulses. When that activity stops, so do you. When that activity changes character, due to injury or drugs, you change character in lockstep. Unlike any other part of your body, if you damage a small piece of the brain, who you are is likely to change radically. To understand how this is possible, let's start at the beginning.

An entire life, lavishly colored with agonies and ecstasies, took place in these three pounds.

Born unfinished

At birth we humans are helpless. We spend about a year unable to walk, about two more before we can articulate full thoughts, and many more years unable to fend for ourselves. We are totally dependent on those around us for our survival. Now compare this to many other mammals. Dolphins, for instance, are born swimming; giraffes learn to stand within hours; a baby zebra can run within forty-five minutes of birth. Across the animal kingdom, our cousins are strikingly independent soon after they're born.

On the face of it, that seems like a great advantage for other species – but in fact it signifies a limitation. Baby animals develop quickly because their brains are wiring up according to a largely preprogrammed routine. But that preparedness trades off with flexibility. Imagine if some hapless rhinoceros found itself on the Arctic tundra, or on top of a mountain in the Himalayas, or in the middle of urban Tokyo. It would have no capacity to adapt (which is why we don't find rhinos in those areas). This strategy of arriving with a pre-arranged brain works inside a particular niche in the ecosystem – but put an animal outside of that niche, and its chances of thriving are low.

In contrast, humans are able to thrive in many different environments, from the frozen tundra to the high mountains to bustling urban centers. This is possible because the human brain is born remarkably unfinished. Instead of arriving with everything wired up – let's call it "hardwired" – a human brain allows itself to be shaped by the details of life experience. This leads to long periods of helplessness as the young brain slowly molds to its environment. It's "livewired".

Childhood pruning: exposing the statue in the marble

What's the secret behind the flexibility of young brains? It's not about growing new cells – in fact, the number of brain cells is the same in children and adults. Instead, the secret lies in how those cells are connected.

At birth, a baby's neurons are disparate and unconnected, and in

LIVEWIRING

Many animals are born genetically preprogrammed, or "hardwired" for certain instincts and behaviors. Genes guide the construction of their bodies and brains in specific ways that define what they will be and how they'll behave. A fly's reflex to escape in the presence of a passing shadow; a robin's preprogrammed instinct to fly south in the winter; a bear's desire to hibernate; a dog's drive to protect its master: these are all examples of instincts and behaviors that are hardwired. Hardwiring allows these creatures to move as their parents do from birth, and in some cases to eat for themselves and survive independently.

In humans the situation is somewhat different. The human brain comes into the world with some amount of genetic hardwiring (for example, for breathing, crying, suckling, caring about faces, and having the ability to learn the details of their native language). But compared to the rest of the animal kingdom, human brains are unusually incomplete at birth. The detailed wiring diagram of the human brain is not preprogrammed; instead, genes give very general directions for the blueprints of neural networks, and world experience fine-tunes the rest of the wiring, allowing it to adapt to the local details.

The human brain's ability to shape itself to the world into which it's born has allowed our species to take over every ecosystem on the planet and begin our move into the solar system.

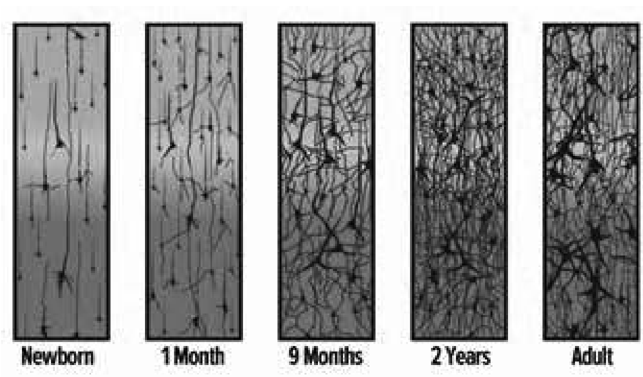
the first two years of life they begin connecting up extremely rapidly as they take in sensory information. As many as two million new connections, or synapses, are formed every second in an infant's brain. By age two, a child has over one hundred trillion synapses, double the number an adult has.

It has now reached a peak and has far more connections than it will need. At this point, the blooming of new connections is supplanted by a strategy of neural "pruning". As you mature, 50% of your synapses will be pared back.

Which synapses stay and which go? When a synapse successfully participates in a circuit, it is strengthened; in contrast, synapses weaken if they aren't useful, and eventually they are eliminated. Just like paths in a forest, you lose the connections that you don't use.

In a sense, the process of becoming who you are is defined by carving back the possibilities that were already present. You become who you are not because of what grows in your brain, but because of what is removed.

Throughout our childhoods, our local environments refine our brain, taking the jungle of possibilities and shaping it back to correspond to what we're exposed to. Our brains form fewer but stronger connections.



In a newborn brain, neurons are relatively unconnected to one another. Over the first two to three years, the branches grow and the cells become increasingly connected. After that, the connections are pruned back, becoming fewer and stronger in adulthood.

As an example, the language that you're exposed to in infancy (say, English versus Japanese) refines your ability to hear the particular sounds of your language, and worsens your capacity to hear the sounds of other languages. That is, a baby born in Japan and a baby born in America can hear and respond to all the sounds in both languages. Through time, the baby raised in Japan will lose the ability to distinguish between, say, the sounds of R and L, two sounds that aren't separated in Japanese. We are sculpted by the world we happen to drop into.

Nature's gamble

Over our protracted childhood, the brain continually pares back its connections, shaping itself to the particulars of its environment. This is a smart strategy to match a brain to its environment – but it also comes with risks.

If developing brains are not given the proper, "expected" environment – one in which a child is nurtured and looked after – the brain will struggle to develop normally. This is something the Jensen family from Wisconsin has experienced first-hand. Carol and Bill Jensen adopted Tom, John, and Victoria when the children were four years old. The three children were orphans who had, until their adoption, endured appalling conditions in state-run orphanages in Romania – with consequences for their brain development.

When the Jensens picked up the children and took a taxi out of Romania, Carol asked the taxi driver to translate what the children were saying. The taxi driver explained they were speaking gibberish. It was not a known language; starved of normal interaction, the children had developed a strange creole. As they've grown up, the children have had to deal with learning disabilities, the scars of their childhood deprivation.

Tom, John, and Victoria don't remember much about their time in Romania. In contrast, someone who remembers the institutions vividly is Dr. Charles Nelson, Professor of Pediatrics at Boston Children's Hospital. He first visited these institutions in 1999. What he saw horrified him. Young children were kept in their cribs, with no sensory stimulation. There was a single caretaker for every fifteen children, and these workers were instructed not to pick the children up or show them affection in any way, even when they were crying – the concern was that such displays of affection would lead to the children wanting more, an impossibility with the limited staffing. In this context, things were as regimented as possible. Children were lined up on plastic pots for toileting. Everyone got the same haircut, regardless of gender. They were dressed alike, fed on schedule. Everything was mechanized.

Children whose cries went unanswered soon learned not to cry. The children were not held and were not played with. Although they had their basic needs met (they were fed, washed and clothed), the infants were deprived of emotional care, support, and any kind of stimulation. As a result, they developed "indiscriminate friendliness". Nelson explains that he'd walk into a room and be surrounded by little kids he'd never seen before – and they'd want to jump into his arms and sit on his lap or hold his hand or walk off with him. Although this sort of indiscriminate behavior seems sweet at first glance, it's a coping strategy of neglected children, and it goes hand-in-hand with long-term attachment issues. It is a hallmark behavior of children who have grown up in an institution.

Shaken by the conditions they were witnessing, Nelson and his team set up the Bucharest Early Intervention Program. They assessed 136 children, aged six months to three years, who had been living in institutions from birth. First, it became clear that the children had IQs in the sixties and seventies, compared to an average of one hundred. The children showed signs of under-developed brains and their language was very delayed. When Nelson used electroencephalography (EEG) to measure the electrical activity

ROMANIA'S ORPHANAGES

In 1966, to increase the population and the work force, Romanian president Nicolae Ceaușescu banned contraception and abortion. State gynecologists known as "menstrual police" examined women of childbearing age to ensure they were producing enough offspring. A "celibacy tax" was levied on families who had fewer than five children. The birth rate skyrocketed.

Many poor families couldn't afford to care for their children – and so they gave them over to state-run institutions. In turn, the state rolled out more institutions to meet the soaring numbers. By 1989, when Ceaușescu was ousted, 170,000 abandoned children resided in institutions.

Scientists soon revealed the consequences of an institutional upbringing on brain development. And those studies influenced government policy. Over the years, most of the Romanian orphans have been returned to their parents or removed to government foster care. By 2005, Romania made it illegal for children to be institutionalized before the age of two, unless severely disabled.

Millions of orphans still live in institutionalized government care around the world. Given the necessity of a nurturing environment for an infant's developing brain, it is imperative that governments find ways to get the children into conditions that allow proper brain development.

in these children's brains, he found they had dramatically reduced neural activity.

Without an environment with emotional care and cognitive stimulation, the human brain cannot develop normally.

Encouragingly, Nelson's study also revealed an important flipside: the brain can often recover, to varying degrees, once the children are removed to a safe and loving environment. The younger a child is removed, the better his recovery. Children removed to foster homes before the age of two generally recovered well. After two, they made improvements – but depending on the age of the child they were left with differing levels of developmental problems.

Nelson's results highlight the critical role of a loving, nurturing environment for a developing child's brain. And this illustrates the profound importance of the environment around us in shaping who we become. We are exquisitely sensitive to our surroundings. Because of the wire-on-the-fly strategy of the human brain, who we are depends heavily on where we've been.

The teen years

Only a couple of decades ago it was thought that brain development was mostly complete by the end of childhood. But we now know that the process of building a human brain takes up to twenty-five years. The teen years are a period of such important neural reorganization and change that it dramatically affects who we seem to be. Hormones coursing around our bodies cause obvious physical changes as we take on the appearance of adults – but out of sight our brains are undergoing equally monumental changes. These changes profoundly color how we behave and react to the world around us.

One of these changes has to do with an emerging sense of self – and with it, self-consciousness.

To get a sense of the teen brain at work, we ran a simple experiment. With the help of my graduate student Ricky Savjani, we asked volunteers to sit on a stool in a shop window display. We then pulled back the curtain to expose the volunteer looking out on the world – to be gawked at by passersby.

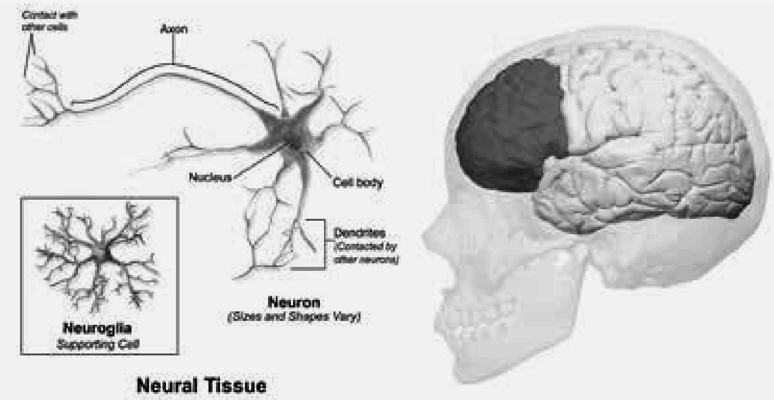
Volunteers sat in a shop window, to be stared at by passersby. Teenagers have greater social anxiety than adults, reflecting the details of brain development during the adolescent years.

Before sending them into this socially awkward situation, we rigged up each volunteer so we'd be able to measure their emotional response. We hooked them up with a device to measure the galvanic skin response (GSR), a useful proxy for anxiety: the more your sweat glands open, the higher your skin conductance will be. (This is, by the way, the same technology used in a lie detector, or polygraph test.)

Both adults and teens participated in our experiment. In adults, we observed a stress response from being stared at by strangers, exactly as expected. But in teenagers, that same experience caused social emotions to go into overdrive: the teens were much more anxious – some to the point of trembling – while they were being watched.

Why the difference between the adults and teens? The answer involves an area of the brain called the medial prefrontal cortex (mPFC). This region becomes active when you think about your self – and especially the emotional significance of a situation to your self. Dr. Leah Somerville and her colleagues at Harvard University found that as one grows from childhood to adolescence, the mPFC becomes more active in social situations, peaking at around fifteen

SCULPTING OF THE ADOLESCENT BRAIN



After childhood, just before the onset of puberty, there is a second period of overproduction: the prefrontal cortex sprouts new cells and new connections (synapses), thereby creating new pathways for molding. This excess is followed by approximately a decade of pruning: all through our teenage years, weaker connections are trimmed back while stronger connections are reinforced. As a result of this thinning out, the volume of the prefrontal cortex reduces by about 1% per year during the teenage years. The shaping of circuits during the teen years sets us up for the lessons we learn on our paths to becoming adults.

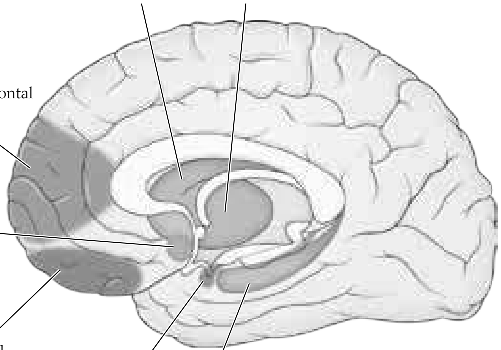
Because these massive changes take place in brain areas required for higher reasoning and the control of urges, adolescence is a time of steep cognitive change. The dorsolateral prefrontal cortex, important for controlling impulses, is among the most belated regions to mature, not reaching its adult state until the early twenties. Well before neuroscientists worked out the details, car insurance companies noticed the consequences of incomplete brain maturation – and they accordingly charge more for teen drivers. Likewise, the criminal justice system has long held this intuition, and thus juveniles are treated differently than adults.

years old. At this point, social situations carry a lot of emotional weight, resulting in a self-conscious stress response of high intensity. That is, in adolescence, thinking about one's self – so-called "self evaluation" – is a high priority. In contrast, an adult brain has grown accustomed to a sense of self – like having broken in a new pair of shoes – and as a result an adult doesn't care as much about sitting in the shop window.

Beyond social awkwardness and emotional hypersensitivity, the teen brain is set up to take risks. Whether it's driving fast or sexting naked photos, risky behaviors are more tempting to the teen brain than to the adult brain. Much of that has to do with the way we respond to rewards and incentives. As we move from childhood into adolescence, the brain shows an increasing response to rewards in areas related to pleasure seeking (one such area is called the nucleus accumbens). In teens, the activity here is as high as it is in adults. But here's the important fact: activity in the orbitofrontal cortex – involved in executive decision making, attention, and simulating future consequences – is still about the same in teens as it is in children. A mature pleasure-seeking system coupled with an immature orbitofrontal cortex means that teens are not only emotionally hypersensitive, but also less able to control their emotions than adults.

Moreover, Somerville and her team have an idea why peer pressure strongly compels behavior in teens: areas involved in social considerations (such as the mPFC) are more strongly coupled to other brain regions that translate motivations into actions (the striatum and its network of connections). This, they suggest, might explain why teens are more likely to take risks when their friends are around.

Due to changes in many brain areas involved in reward, planning, and motivation, our sense of self undergoes major changes in our teenage years.



How we see the world as a teenager is the consequence of a changing brain that's right on schedule. These changes lead us to be more self-conscious, more risk-taking, and more prone to peer-motivated behavior. For frustrated parents the world over, there's an important message: who we are as a teenager is not simply the result of a choice or an attitude; it is the product of a period of intense and inevitable neural change.

Plasticity in adulthood

By the time we're twenty-five years of age, the brain transformations of childhood and adolescence are finally over. The tectonic shifts in our identity and personality have ended, and our brain appears to now be fully developed. You might think that who we are as adults is now fixed in place, immoveable. But it's not: in adulthood our brains continue to change. Something that can be shaped – and can hold that shape – is what we describe as plastic. And so it is with the brain, even in adulthood: experience changes it, and it retains the change.

To get a sense of how impressive these physical changes can be, consider the brains of a particular group of men and women who