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NEUROSCIENCE

the *amazing* teen brain

A mismatch in the maturation of brain networks leaves adolescents open to risky behavior but also allows for leaps in cognition and adaptability

By Jay N. Giedd

IN BRIEF

MRI studies show that the teenage brain is not an old child brain or a half-baked adult brain; it is a unique entity characterized by changeability and an increase in networking among brain regions.

The limbic system, which drives emotions, intensifies at puberty, but the prefrontal cortex, which controls impulses, does not mature until the 20s. This mismatch makes teens prone to risk taking but also allows them to adapt readily to their environment.

Earlier onset of puberty in children worldwide is expanding the years during which the mismatch occurs.

Greater understanding of the teen brain should help parents and society better distinguish typical behavior from mental illness while helping teens become the people they want to be.

Illustration by Harry Campbell, Photograph by Ethan Hill

The "teen brain" is often ridiculed as an oxymoron—an example of biology gone wrong.

Neuroscientists have explained the risky, aggressive or just plain baffling behavior of teenagers as the product of a brain that is somehow compromised. Groundbreaking research in the past 10 years, however, shows that this view is wrong. The teen brain is not defective. It is not a half-baked adult brain, either. It has been forged by evolution to function differently from that of a child or an adult.

Foremost among the teen brain's features is its ability to change in response to the environment by modifying the communications networks that connect brain regions. This special changeability, or plasticity, is a double-edged sword. It allows teenagers to make enormous strides in thinking and socialization. But the morphing landscape also makes them vulnerable to dangerous behaviors and serious mental disorders.

The most recent studies indicate that the riskiest behaviors arise from a mismatch between the maturation of networks in the limbic system, which drives emotions and becomes turbo-boosted in puberty, and the maturation of networks in the prefrontal cortex, which occurs later and promotes sound judgment and the control of impulses. Indeed, we now know that the prefrontal cortex continues to change prominently until well into a person's 20s. And yet puberty seems to be starting earlier, extending the "mismatch years."

The plasticity of networks linking brain regions—and not the growth of those regions, as previously thought—is key to eventually behaving like an adult. Understanding that, and knowing that a widening gap between the development of emotional and judgment networks is happening in young people today, can help parents, teachers, counselors and teenagers themselves. People will better see that behaviors such as risk taking, sensation seeking, and turning away from parents and toward peers are not signs of cognitive or emotional problems. They are a natural result of brain development, a normal part of adolescents learning how to negotiate a complex world.

The same understanding can also help adults decide when to intervene. A 15-year-old girl's departure from her parents' tastes in clothing, music or politics may be a source of consternation for Mom and Dad but does not indicate mental illness. A 16-year-old boy's propensity to skateboard without a helmet or to accept risky dares from friends is not trivial but is more likely a manifestation of short-range thinking and peer pressure than a desire to hurt himself. Other exploratory and aggressive actions might be red flags, however. Knowing more about the unique teen brain will help all of us learn how to separate unusual behavior that is age-appropriate from that which might indicate illness. Such awareness could help society reduce the rates of teen addiction, sexually transmitted diseases, motor vehicle accidents, unwanted pregnancy, homicide, depression and suicide.

GREATER CONNECTIVITY

FEW PARENTS OF A TEENAGER will be surprised to hear that the brain of a 16-year-old is different from the brain of an eight-year-old. Yet researchers have had difficulty pinning down these differences in a scientific way. Wrapped in a tough, leathery membrane, surrounded by a protective moat of fluid and completely encased in bone, the brain is well protected from falls, attacks from predators—and the curiosity of scientists.

The invention of imaging technologies such as computerized tomography and positron-emission tomography has offered some progress, but because these techniques emit ionizing radiation, it was unethical to use them for exhaustive studies of youth. The advent of magnetic resonance imaging (MRI) finally provided a way to lift the veil, offering a safe and accurate way to study the anatomy and physiology of the brain in people of all ages. Ongoing studies are tracking thousands of twins and single individuals throughout their lives. The consistent theme that is emerging is that the adolescent brain does not mature by getting larger; it matures by having its different components become more interconnected and by becoming more specialized.

In MRI scans, the increase in connectivity among brain regions is indicated as greater volumes of white matter. The "white" in white matter comes from a fatty substance called myelin, which wraps and insulates the long wire, or axon, that extends from a neuron's body. Myelination—the formation of this fatty sheath—takes place from childhood through adulthood and significantly speeds up the conduction of nerve impulses among neurons. Myelinated axons transmit signals up to 100 times faster than unmyelinated ones.

Myelination also accelerates the brain's information processing by helping axons recover quickly after they fire so that they are ready to send another message. Quicker recovery time allows up to a 30-fold increase in the frequency with which a given neuron can transmit information. The combination of faster transmission and shorter recovery time provides a 3,000-fold increase in the brain's computational bandwidth between infancy and adulthood, permitting extensive and elaborate networking among brain regions.

Recent investigations are revealing another, more nuanced

PAGE 33: GROOMING BY TINNA EMPERA *Cloutier/Remix*; STYLING BY MONICA COTTO; PHOTOGRAPH FOR ILLUSTRATION PURPOSES ONLY
SOURCE: "DEVELOPMENT OF BRAIN STRUCTURAL CONNECTIVITY BETWEEN AGES 12 AND 30," BY EMILY L. DENNIS ET AL., IN *NEUROIMAGE*, VOL. 64; JANUARY 1, 2013 (SUPPLEMENTARY VIDEO 2)

role for myelin. Neurons integrate information from other neurons but only fire to pass it on if the incoming input exceeds a certain electrical threshold. If the neuron fires, that action initiates a series of molecular changes that strengthens the synapses, or connections, between that neuron and the input neurons.

This strengthening of connections forms the basis for learning. What researchers themselves are now learning is that for input from nearby and distant neurons to arrive simultaneously at a given neuron, the transmission must be exquisitely timed, and myelin is intimately involved in the fine-tuning of this timing. As children become teenagers, the rapid expansion of myelin increasingly joins and coordinates activities in different parts of the brain on a variety of cognitive tasks.

Scientists can now measure this changing interconnectivity by applying graph theory, a type of mathematics that quantifies the relation between "nodes" and "edges" in a network. Nodes can be any object or detectable entity, such as a neuron or a brain structure like the hippocampus or a larger region such as the prefrontal cortex. Edges can be any connections among nodes, from a physical connection such as a synapse between neurons to a statistical correlation such as when two parts of the brain are activated similarly during a cognitive task.

Graph theory has helped me and others to measure how different brain regions develop and become interconnected to one another and to correlate such features with changes in behavior and cognition. Brain changes are not confined to adolescence. Most brain circuits develop in the womb, and many continue to change throughout life, well beyond the teen years. It turns out, however, that during that period there is a dramatic increase in connectivity among brain regions involved in judgment, getting along with others and long-range planning—abilities that profoundly influence the remainder of a person's life.

TIME TO SPECIALIZE

AS THE WHITE MATTER along neurons is developing with age in adolescents, another change is taking place. Brain development, like other complex processes in nature, proceeds by a one-two punch of overproduction, followed by selective elimination. Like Michelangelo's *David* emerging from a block of marble, many cognitive advances arise during a sculpting process in which unused or maladaptive brain cell connections are pruned away. Frequently used connections, meanwhile, are strengthened. Although pruning and strengthening occur throughout our lives, during adolescence the balance shifts to elimination, as the brain tailors itself to the demands of its environment.

Specialization arises as unused connections among neurons are eliminated, decreasing the brain's gray matter. Gray matter consists largely of unmyelinated structures such as neuron cell bodies, dendrites (antennalike projections from the cells that receive information from other neurons) and certain axons. Overall, gray matter increases during childhood, reaches a maximum around age 10 and declines through adolescence. It levels off during adulthood and declines somewhat further in senescence. The pattern also holds for the density of receptor cells on neurons that respond to neurotransmitters—molecules such as dopamine, serotonin and glutamate that modulate communication among brain cells.

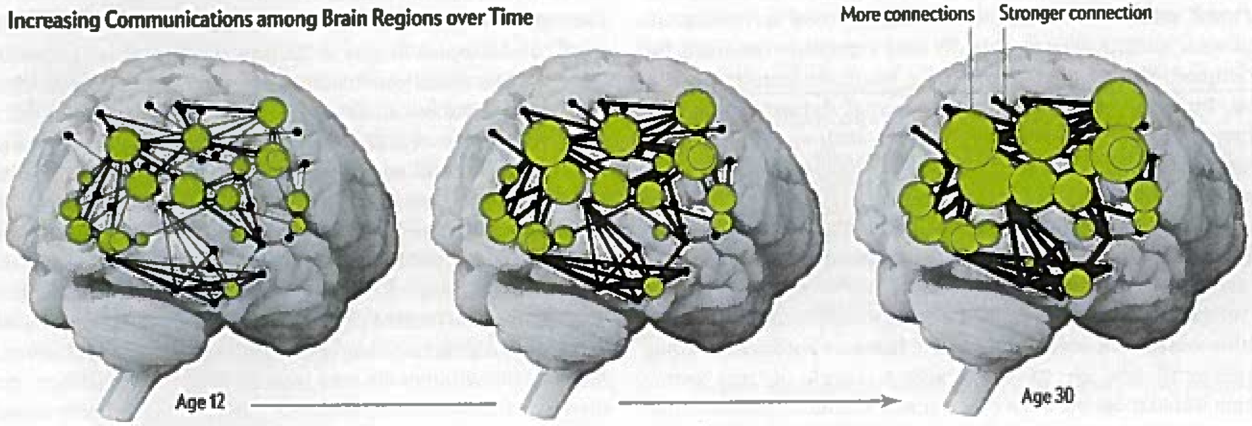
Although the raw amount of gray matter tops out around puberty, full development of different brain regions occurs at different times. Gray matter, it turns out, peaks earliest in what are called primary sensorimotor areas devoted to sensing and responding to sight, sound, smell, taste and touch. It peaks latest in the prefrontal cortex, crucial to executive functioning, a term that encompasses a broad array of abilities, including organization, decision making and planning, along with the regulation of emotion.

A NEW VIEW

Greater Networking Brings Maturity

The most significant change taking place in an adolescent brain is not the growth of brain regions but the increase in communications among groups of neurons. When an analytical technique called graph theory is applied to data from MRI scans, it shows that from ages 12 to 30, connections between certain brain regions or neuron groups become stronger (*black lines that get thicker*). The analysis also shows that certain regions and groups become more widely connected (*green circles that get larger*). These changes ultimately help the brain to specialize in everything from complex thinking to being socially adept.

Increasing Communications among Brain Regions over Time



STRUCTURAL CONNECTIVITY BETWEEN AGES 12 AND 30," BY EMILY L. DENNIS ET AL., IN NEUROIMAGE, VOL. 64; JANUARY 1, 2013 (SUPPLEMENTARY VIDEO 2)

Illustration by David Killpack (brains) and Jen Christiansen (nodal diagrams)

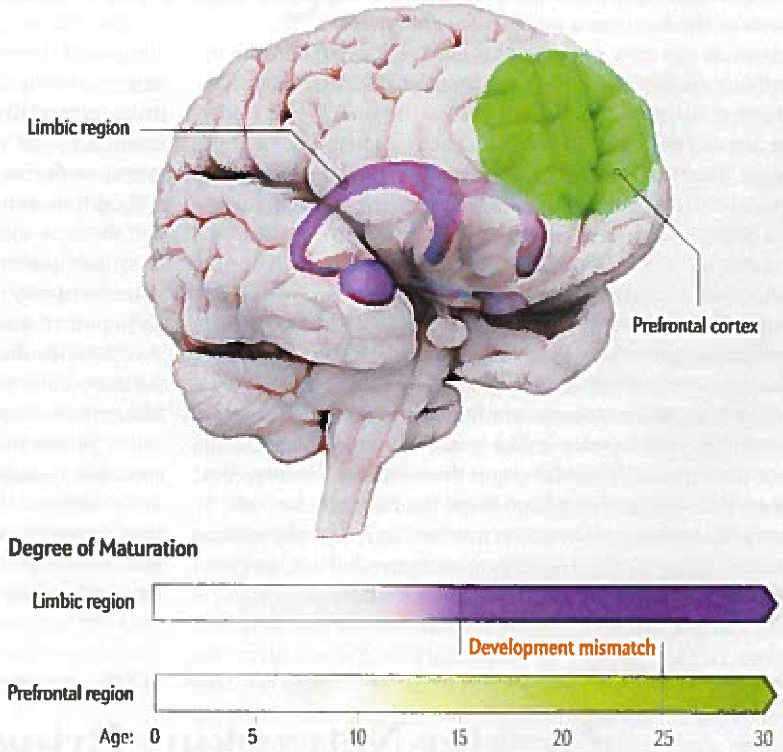
An important feature of the prefrontal cortex is the ability to create hypothetical what-ifs by mental time travel—to consider past, present and possible future outcomes by running simulations in our mind instead of subjecting ourselves to potentially dangerous reality. As philosopher Karl Popper phrased it, instead of putting ourselves in harm's way, "our theories die in our stead." As we mature cognitively, our executive functioning also makes us more likely to choose larger, longer-term rewards over smaller, shorter-term ones.

The prefrontal cortex is also a key component of circuitry involved in social cognition—our ability to navigate complex social relationships, discern friend from foe, find protection within groups and carry out the prime directive of adolescence: to attract a mate.

Adolescence is therefore marked by changes in gray matter and in white matter that together transform the networking among brain regions as the adult brain takes shape. The prefrontal cortex functions are not absent in teenagers; they are just not as good as they are going to get. Because they do not fully mature until a person's 20s, teens may have trouble controlling impulses or judging risks and rewards.

Emotion vs. Control

Teenagers are more likely than children or adults to engage in risky behavior, in part because of a mismatch between two major brain regions. Development of the hormone-fueled limbic system (*purple*), which drives emotions, intensifies as puberty begins (typically between ages 10 to 12), and the system matures over the next several years. But the prefrontal cortex (*green*), which keeps a lid on impulsive actions, does not approach full development until a decade later, leaving an imbalance during the interim years. Puberty is starting earlier, too, boosting hormones when the prefrontal cortex is even less mature.



SOURCE: JAY N. GIEDD

A MISMATCH IN MATURATION

UNLIKE THE PREFRONTAL CORTEX, the hormone-fueled limbic system undergoes dramatic changes at the time of puberty, which traditionally begins between ages 10 and 12. The system regulates emotion and feelings of reward. It also interacts with the prefrontal cortex during adolescence to promote novelty seeking, risk taking and a shift toward interacting with peers. These behaviors, deeply rooted in biology and found in all social mammals, encourage tweens and young teens to separate from the comfort and safety of their families to explore new environments and seek outside relationships. These behaviors diminish the likelihood of inbreeding, creating a healthier genetic population, but they can also pose substantial dangers, especially when mixed with modern temptations such as easy access to drugs, firearms and high-speed motor vehicles, unchecked by sound judgment.

What most determines teen behavior, then, is not so much the late development of executive functioning or the early onset of emotional behavior but a mismatch in the timing of the two developments. If young teens are emotionally propelled by the limbic system, yet prefrontal control is not as good as it is going to get until, say, age 25, that leaves a decade of time during which imbalances between emotional and contemplative thinking can reign. Furthermore, puberty starting at an earlier age, as is the case worldwide, lengthens the gap of time between the onset of increased risk taking and sensation seeking and the rise of a strong, stabilizing prefrontal cortex.

The lengthening mismatch supports the growing notion that the teen years are no longer synonymous with adolescence. Adolescence, which society defines as the transition from childhood to adulthood, begins in biology with the onset of puberty but ends in a social construct when a person achieves independence and assumes adult roles. In the U.S., attainment of an adult role—often characterized by such events as getting married, having a child and owning a home—is occurring approximately five years later than in the 1970s.

The large influence of social factors in determining what constitutes an adult has led some psychologists to suggest that adolescence is less of a biological reality than a product of changes in child rearing since the industrial revolution. Yet twin studies, which examine the relative effects of genes and environment by following twins who have different experiences, refute the view that social factors can substantially override the biology. They show that the pace of biological maturation of white

Illustration by David Killpack (brain) and Jen Christiansen (graphic) and gray matter can be influenced somewhat by the environment but that the fundamental timing is under biological control. Sociologists see this, too; risk taking, sensation seeking and a move toward peers happen in all cultures, although the degree can vary.

VULNERABILITY AND OPPORTUNITY

THE GRAY MATTER, white matter and networking developments detected by MRI underscore the observation that the most striking feature in teen brain development is the extensive changes that occur. In general, this plasticity decreases throughout adulthood, and yet we humans still retain a level of plasticity far longer than any other species.

Protracted maturation and prolonged plasticity allow us to "keep our options open" in the course of our own development, as well as the entire species' evolution. We can thrive everywhere from the frigid North Pole to hot islands on the equator. With technologies developed by our brain, we can even live in vessels orbiting our planet. Back 10,000 years ago—a blink of an eye in evolutionary terms—we spent much of our time securing food and shelter. Today many of us spend most of our waking hours dealing with words and symbols—which is particularly noteworthy, given that reading is only 5,000 years old.

Prolonged plasticity has served our species well but creates vulnerabilities in addition to opportunities. Adolescence is the peak time of emergence for several types of mental illnesses, including anxiety disorders, bipolar disorder, depression, eating disorders, psychosis and substance abuse. Surprisingly, 50 percent of the mental illnesses people experience emerge by age 14, and 75 percent start by age 24.

The relation between typical adolescent brain changes and the onset of psychopathology is complicated, but one underlying theme may be that "moving parts get broken." The idea is that the extensive changes in white matter, gray matter and networking increase the chance for problems to arise. For example, almost all the abnormal brain findings in adult schizophrenia resemble the typical changes of adolescent brain development gone too far.

In many other ways, adolescence is the healthiest time of life. The immune system, resistance to cancer, tolerance to heat and cold, and other traits are at their greatest. Despite physical robustness, however, serious illness and death are 200 to 300 percent higher for teens than for children. Motor vehicle accidents, the number-one cause, account for about half of teen deaths. Homicide and suicide rank second and third. Unwanted teen pregnancy, sexually transmitted diseases and behavior leading to incarceration are also high, imposing tough, lifelong consequences.

So what can doctors, parents, teachers and teens themselves do about these pitfalls? For clinicians, the paucity of novel medications in psychiatry and the propensity of the adolescent brain to respond to environmental challenges suggest that nonmedication interventions may be most fruitful—especially early in teen development, when white matter, gray matter and networking are changing fast. Treatment of obsessive-compulsive disorder is one example; behavioral interventions that trigger the obsessive impulse but gradually modify a person's response may be highly effective and could prevent a lifetime of disability. Appreciating that the brain is changeable throughout the teen years obliterates the notion that a youth is a "lost cause." It offers optimism that interventions can change a teenager's life course.

More study will help, too. The infrastructure for adolescent research is not well developed, funding for this work is meager and few neuroscientists specialize in this age group. The good news is that as researchers clarify the mechanisms and influences of adolescent brain developments, more resources and scientists are being drawn into the field, eager to minimize risks for teenagers and harness the incredible plasticity of the teen brain.

Understanding that the adolescent brain is unique and rapidly changing can help parents, society and teens themselves to better manage the risks and grasp the opportunities of the teenage years. Knowing that prefrontal executive functions are still under construction, for example, may help parents to not overreact when their daughter suddenly dyes her hair orange and instead take solace in the notion that there is hope for better judgment in the future. Plasticity also suggests that constructive dialogue between parents and teens about issues such as freedoms and responsibilities can influence development.

Adolescents' inherent capacity to adapt raises questions about the impact of one of the biggest environmental changes in history: the digital revolution. Computers, video games, cell phones and apps have in the past 20 years profoundly affected the way teens learn, play and interact. Voluminous information is available, but the quality varies greatly. The skill of the future will not be to remember facts but to critically evaluate a vast expanse of data, to discern signal from noise, to synthesize content and to apply that synthesis to real-world problem solving. Educators should challenge the adolescent brain with these tasks, to train its plasticity on the demands of the digital age.

Greater society has some compelling opportunities as well. For one thing, it could be more focused on harnessing the passion, creativity and skills of the unique adolescent development period. Society should also realize that the teen years are a turning point for a life of peaceful citizenship, aggression or, in rare cases, radicalization. Across all cultures, adolescents are the most vulnerable to being recruited as soldiers and terrorists, as well as the most likely to be influenced to become teachers and engineers. Greater understanding of the teen brain could also help judges and jurors reach decisions in criminal trials.

For teens themselves, the new insights of adolescent neuroscience should encourage them to challenge their brain with the kinds of skills that they want to excel at for the remainder of their lives. They have a marvelous opportunity to craft their own identity and to optimize their brain according to their choosing for a data-rich future that will be dramatically different from the present lives of their parents. ■

MORE TO EXPLORE

The Primal Teen: What the New Discoveries about the Teenage Brain Tell Us about Our Kids. Barbara Strauch. Doubleday, 2003.

Development of Brain Structural Connectivity between Ages 12 and 30: A 4-Tesla Diffusion Imaging Study in 439 Adolescents and Adults. Emily L. Dennis et al. in *NeuroImage*, Vol. 64, pages 671–684; January 1, 2013.

Age of Opportunity: Lessons from the New Science of Adolescence. Laurence Steinberg. Houghton Mifflin Harcourt, 2014.

FROM OUR ARCHIVES

The Myth of the Teen Brain. Robert Epstein; *Scientific American Mind*, April/May 2007.

scientificamerican.com/magazine/sa

SCIENTIFIC AMERICAN ONLINE For a review of the effectiveness of punishments for juvenile offenders, see ScientificAmerican.com/jun2015/giedd