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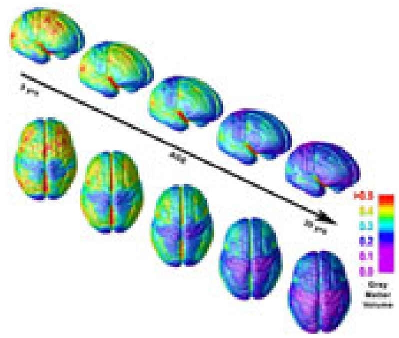

Different parts of the brain mature at varying rates during adolescence. This image indicates an average decrease in gray matter volumes between ages 5 and 20, thanks to the pruning of neural connections. Areas that mediate "executive functioning" mature later than areas responsible for basic functions. (Image courtesy of Jay N. Giedd, M.D.)

The Teen Brain: Primed to Learn, Primed to Take Risks

By: Jay N. Giedd, M.D.

The changes the brain undergoes during adolescence pave the way to adulthood, priming the young person for life away from home and for finding unrelated mates. But this plasticity also can open the door to poor decision making and risky behavior, writes Jay N. Giedd, a child psychiatrist at the National Institute of Mental Health.

More Information:

View a time-lapse video of changes in the brain from age 5 to age 20. (on Lab of Neuro Imaging, UCLA School of Medicine, site)

Webcast: The Teen Brain, with panelists Jay Giedd, Kay Redfield Jamison and Stephen Maistro

Brief: Brain Development in a Hyper-Tech World

During adolescence the brain's ability to change is especially pronounced—and that can be a double-edged sword. Jay N. Giedd, a *child and adolescent psychiatrist at the National Institute of Mental Health who specializes in brain imaging, points out that the brain's plasticity allows adolescents to learn and adapt, which paves the way for independence. But it also poses dangers: different rates of development can lead to poor decision making, risk taking—and, in some cases, diagnosable disorders.*

Across cultures and millennia, the teen years have been noted as a time of dramatic changes in body and behavior. During this time most people successfully navigate the transition from depending upon family to becoming a self-sufficient adult member of the society. However, adolescence is also a time of increased conflicts with parents, mood volatility, risky behavior and, for some, the emergence of psychopathology.

and well described. The brain's transformation is every bit as dramatic but, to the unaided eye, is visible only in terms of new and different behavior. The teen brain is not broken or defective. Rather, it is wonderfully optimized to promote our success as a species.

Beginning in childhood and continuing through adolescence, dynamic processes drive brain development, creating the flexibility that allows the brain to refine itself, specialize and sharpen its functions for the specific demands of its environment. Maturing connections pave the way for increased communication among brain regions, enabling greater integration and complexity of thought. When what we call adolescence arrives, a changing balance between brain systems involved in emotion and regulating emotion spawns increased novelty seeking, risk taking and a shift toward peer-based interactions.

These behaviors, found in all social mammals, encourage separating from the comfort and safety of our families to explore new environments and seek unrelated mates.[1] However, these potentially adaptive behaviors also pose substantial dangers, especially when mixed with modern temptations and easy access to potent substances of abuse, firearms and high-speed motor vehicles.

In many ways adolescence is the healthiest time of life. The immune system, resistance to cancer, tolerance for heat and cold and several other variables are at their peak. Despite physical strengths, however, illness and mortality increase 200 percent to 300 percent. As of 2005, the most recent year for which statistics are available, motor vehicle accidents, the No. 1 cause, accounted for about half of deaths. Nos. 2 and 3 were homicide and suicide.[2] Understanding this healthy-body, risk-taking-brain paradox will require greater insight into how the brain changes during this period of life. Such enhanced understanding may help to guide interventions when illnesses emerge or to inform parenting or educational approaches to encourage healthy development.

Adolescent Neurobiology: Three Themes

The brain, the most protected organ of the body, has been particularly opaque to investigation of what occurs during adolescence. But now the picture emerging from the science of adolescent neurobiology highlights both the brain's capacity to handle increasing cognitive complexity and an enormous potential for plasticity—the brain's ongoing ability to change. The advent of structural and functional magnetic resonance imaging (MRI), which combines a powerful magnet, radio waves, and sophisticated computer technology to provide exquisitely accurate pictures of brain anatomy and physiology, has opened an unprecedented window into the biology of the brain, including how its tissues function and how particular mental or physical activities change blood flow. Because the technique does not use ionizing radiation, it is well suited for pediatric studies and has launched a new era of neuroscience. Three themes emerge from neuroimaging research in adolescents:

1. Brain cells, their connections and receptors for chemical messengers called neurotransmitters peak during childhood, then decline in adolescence.
2. Connectivity among brain regions increases.
3. The balance among frontal (executive-control) and limbic (emotional) systems changes.

These themes appear again and again in our studies of the biological underpinnings for cognitive and behavioral changes in teenagers.

Theme 1: Childhood Peaks Followed by Adolescent Declines in Cells, Connections and Receptors

The brain's 100 billion neurons and quadrillion synapses create a multitude of potential connection patterns. As teens interact with the unique challenges of their environment, these connections form and re-form, giving rise to specific behaviors—with positive or negative outcomes. This plasticity is the essence of adolescent neurobiology and underlies both the enormous learning potential and the vulnerability of the teen years.

Neuroimaging reveals that gray matter volumes—which reflect the size and number of branches of brain cells—increase during childhood, peak at different times depending on the location in the brain, decline through adolescence, level off during adulthood and then decline somewhat further in senescence. This pattern of childhood peaks followed by adolescent declines occurs not only in gray matter volumes but also in the number of synapses and the densities of neurotransmitter receptors.[3] This one-two punch—overproduction followed by competitive elimination—drives complexity not only in brain development but also across myriad natural systems.

Theme 2: Increased Connectivity

Many cognitive advances during adolescence stem from faster communication in brain circuitry and increased integration of brain activity. To use a language metaphor, brain maturation is not so much a matter of adding new letters as it is one of combining existing letters into words, words into sentences and sentences into paragraphs.

"Connectivity" characterizes several neuroscience concepts. In anatomic studies connectivity can mean a physical link between areas of the brain that share common developmental trajectories. In studies of brain function, connectivity describes the relationship between different parts of the brain that activate together during a task. In genetic studies it refers to different regions that are influenced by the same genetic or environmental factors. All of these types of connectivity increase during adolescence.

In structural magnetic resonance imaging studies of brain anatomy, connectivity, as indicated by the volume of white matter—bundles of nerve cells' axons, which link various regions or areas of the brain—increases throughout childhood and adolescence and continues to grow until women reach their 40s and men their 30s. The foundation of this increase in wiring is myelination, the formation of a fatty sheath of electrical insulation around axons, which speeds conduction of nerve impulses. The increase is not subtle—myelinated axons transmit impulses up to 100 times faster than unmyelinated axons. Myelination also accelerates the brain's information processing via a decrease in the recovery time between firings. That allows up to a 30-fold increase in the frequency with which a given neuron can transmit information. This combination—the increase in speed and the decrease in recovery time—is roughly equivalent to a 3,000-fold increase in computer bandwidth.

However, recent investigations into white matter are revealing a much more nuanced role for myelin than a simple "pedal to the metal" increase in transmission speed. Neurons integrate information from other neurons by summing excitatory and inhibitory input. If excitatory input exceeds a certain threshold, the receiving neuron fires and initiates a series of molecular changes that strengthens the synapses, or connections, from the input neurons. Donald Hebb famously described this process in 1940 as "cells that fire together wire together." It forms the basis for learning. In order for input from nearby and more distant neurons to arrive simultaneously, the transmission must be exquisitely timed. Myelin is intimately involved in the fine-tuning of this timing, which encodes the basis for thought, consciousness and meaning in the brain. The dynamic activity of myelination during adolescence reflects how much new wiring is occurring.

On the flip side, recent research reveals that myelination also helps close the windows of plasticity by inhibiting axon sprouting and the creation of new synapses.[4] Thus, as myelination proceeds, circuitry that is used the most becomes faster, but at the cost of decreased plasticity.

Advances in imaging techniques such as diffusion tensor imaging (DTI) and magnetization transfer (MT) imaging have helped spark interest in these processes by allowing researchers to characterize the direction of axons and the microstructure of white matter. These new techniques further confirm an increase in white matter organization during adolescence, which correlates in specific brain regions with improvements in language,[5] reading,[6] ability to inhibit a response[7] and memory.[5]

Functional magnetic resonance imaging studies also consistently demonstrate increasing and more efficient communication among brain regions during child and adolescent development. We can measure this communication by comparing regions' activation during a task. In studies assessing memory[8] and resistance to peer pressure,[9] the efficiency of communication in the relevant circuitry was a better predictor of how teens performed than was a measurement of metabolic activity in the regions involved.

These lines of investigation, along with EEG studies indicating increased linking of electrical activity in different brain regions, converge to establish a fundamental maturation pattern in the brain: an increase in cognitive activity that relies on tying together and integrating information from multiple sources. These changes allow for greater complexity and depth of thought.

Theme 3: Changing Frontal/Limbic Balance

The relationship between earlier-maturing limbic system networks, which are the seat of emotion, and later-maturing frontal lobe networks, which help regulate emotion, is dynamic. Appreciating the interplay between limbic and cognitive systems is imperative for understanding decision making during adolescence. Psychological tests are usually conducted under conditions of "cold cognition"—hypothetical, low-emotion situations. However, real-world decision making often occurs under conditions of "hot cognition"—high arousal, with peer pressure and real consequences. Neuroimaging investigations continue to discern the different biological circuitry involved in hot and cold cognition and are beginning to map how the parts of the brain involved in decision making mature.

Frontal lobe circuitry mediates “executive functioning,” a term encompassing a broad array of abilities, including attention, response inhibition, regulation of emotion, organization and long-range planning. Structural MRI studies of cortical thickness indicate that areas involved in high-level integration of input from disparate parts of the brain mature particularly late and do not reach adult levels until the mid 20s (see the image that accompanies this article, and the video here).[10]

Across a wide variety of tasks, fMRI studies consistently show an increasing proportion of frontal versus striatal or limbic activity as we progress from childhood to adulthood. For example, among 37 study participants aged 7–29, the response to rewards in the nucleus accumbens (related to pleasure seeking) of adolescents was equivalent to that in adults, but activity in the adolescent orbitofrontal cortex (involved in motivation) was similar to that in children.[11] The changing balance between frontal and limbic systems helps us understand many of the cognitive and behavioral changes of adolescence.

Normal Changes versus Pathology

One of the greatest challenges for parents and others who work with teens is to distinguish sometimes exasperating behavior from genuine pathology. Against the backdrop of healthy adolescence, which includes a wide range of mood fluctuations and occasional poor judgment, is the reality that many types of pathology emerge during adolescence, including anxiety disorders, bipolar disorder, depression, eating disorders, psychosis, and substance abuse. The relationship between normal neurobiological variations and the onset of psychopathology is complicated, but one underlying theme may be that “moving parts get broken.” In other words, development may go awry, predisposing adolescents to disorders. Although neuroimaging is beginning to establish correlations between brain structure or function and behavior, a link between typical behavioral variations and psychopathology has not been firmly established. For example, the neural circuitry underlying teen moodiness may not be the same circuitry involved in depression or bipolar disorder. A greater understanding of the relationship between specific adolescent brain changes and their specific cognitive, behavioral and emotional consequences may provide insight into prevention or treatment.

In the meantime, late maturation of the prefrontal cortex, which is essential in judgment, decision making and impulse control, has prominently entered discourse affecting the social, legislative, judicial, parenting and educational realms. Despite the temptation to trade the complexity and ambiguity of human behavior for the clarity and aesthetic beauty of colorful brain images, we must be careful not to over-interpret the neuroimaging findings as they relate to public policy. Age-of-consent questions are particularly enmeshed in political and social contexts. For example, currently in the United States a person must be at least 15 to 17 years old (depending on the state) to drive, at least 18 to vote, buy cigarettes, or be in the military, and at least 21 to drink alcohol. The minimum age for holding political office varies as well: some municipalities allow mayors as young as 16, and the minimum age for governors ranges from 18 to 30. (On the national level, 25 is the minimum age to be a member of the U.S. House of Representatives, and 35 to be a senator or the president.) The age to consent to sexual relations varies worldwide from puberty (with no specific age attached) to age 18. In most laws the age at which a female can consent to sexual relations is lower than the age for a male. In the United States the legal age to consent to sexual intercourse varies by state from 14 to 17 for females and from 15 to 18 for males. Clearly, these demarcations reflect strong societal influences and do not pinpoint a biological "age of maturation." For instance, the age of majority was increased from 15 to 21 in 13th-century England because one needed both to be strong enough to bear the weight of protective armor and to acquire the necessary skills for combat. Societal influences also contributed to the 26th Amendment to the United States Constitution, which in 1971 lowered the voting age from 21 to 18 to address the discrepancy between being able to be drafted and being able to vote. Delineating the proper role of developmental neuroscience, particularly neuroimaging, in informing public policy on age-of-consent issues will require extensive deliberation with input from many disciplines.

From the perspective of evolutionary adaptation, it is not surprising that the brain is particularly changeable during adolescence—a time when we need to learn how to survive independently in whatever environment we find ourselves. Humans can survive in the frozen tundra of the North Pole or in the balmy tropics on the equator. With the aid of technologies that began as ideas from our brains, we can even survive in outer space. Ten thousand years ago, a blink of an eye in evolutionary time spans, our brains may have been optimized for hunting or for gathering berries. Now our brains may be fine-tuned for reading or programming computers. This incredible changeability, or plasticity, of the human brain is perhaps the most distinctive feature of our species. It makes adolescence a time of great risk and great opportunity.

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