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Inside the teen brain

Behavior can be baffling when young minds are taking shape

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One day, your child is a beautiful, charming 12-year-old, a kid who pops out of bed full of good cheer, clears the table without being asked, and brings home good grades from school. The next day, your child bursts into tears when you ask for the salt and listens to electronic music at maximum volume for hours on end. Chores? Forget it. Homework? There's little time, after talking to friends on the phone for five hours every night. **Mornings? Your bluebird of happiness is flown, replaced by a groaning lump that can scarcely be roused for school.** In short, your home is now inhabited by a teenager.

The shootings in Littleton, Colo., focused the nation's attention on aberrant adolescent behavior, but most teens never come close to committing violent acts. Still, even the most easygoing teenagers often confound their elders with behavior that seems odd by adult standards.

For most of this century, the assumption has been that teenage sturm and drang, the insolence and the rages, are all directed at parents. Teens turn against authority figures, went the conventional wisdom, in an effort to define who they are and to assert their independence--a view that spawned the teenage rebel, that quintessential American icon. The alternative explanation was that hormones, those glandular bringers of sexual stirrings and pimples, were to blame.

The true source of teenage behavior lies north of the gonads. It's that 3-pound blob of gray and white matter known as the brain.

Yes, teenagers do have brains, but theirs don't yet function like an adult's. With the advent of technologies such as magnetic resonance imaging,

neuroscientists have discovered that the adolescent brain is far from mature. "The teenage brain is a work in progress," says Sandra Witelson, a neuroscientist at McMaster University in Ontario, and it's a work that develops in fits and starts.

Until the past decade, neuroscientists believed that the brain was fully developed by the time a child reached puberty and that the 100 billion neurons, or nerves, inside an adult's skull--the hardware of the brain--were already in place by the time pimples began to sprout. The supposition was that a teenager could think like an adult if only he or she would cram in the necessary software--a little algebra here, some Civil War history there, capped by proficiency in balancing a checkbook. **But the neural circuitry, or hardware, it turns out, isn't completely installed in most people until their early 20s.**

And just as a teenager is all legs one day and all nose and ears the next, different regions of his brain are developing on different timetables. For instance, one of the last parts to mature is in charge of making sound judgments and calming unruly emotions. And the emotional centers in the teenage brain have already been revving up, probably under the influence of sex hormones.

This imbalance may explain why your intelligent 16-year-old doesn't think twice about getting into a car driven by a friend who is drunk, or why your formerly equable 13-year-old can be hugging you one minute and then flying off the handle the next.

Indeed, the brain inside a teenager's skull is in some ways closer to a child's brain than to an adult's. Still being forged are the connections between neurons that affect not only emotional skills but also physical and mental abilities. **That means that it might be unreasonable to expect young teenagers to organize multiple tasks or grasp abstract ideas.** And these still-developing neural links leave a teenager vulnerable: Depression in adolescence may set up circuits in the brain that will make it much harder to treat the illness later in life.

But these changes aren't all for the worse. The brain's capacity for growth through adolescence may also indicate that even troubled teenagers can still learn restraint, judgment, and empathy. "Adolescence is a time of tumultuous change in the brain," says Jay Giedd, a child psychiatrist at the National Institute of Mental Health in Bethesda, Md. "Teenagers are choosing what their brains are going to be good at--learning right from wrong, responsibility or impulsiveness, thinking or video games."

If there's one thing that drives parents nuts about their teenagers, it's moodiness. "It's hot and cold, nasty and nice," says Vicki Sasso, 34, the mother of 13-year-old Angelo, a ninth grader from Staten Island, N.Y. "One minute loving me, one minute hating me." Don't blame Angelo; blame the parts of his brain that process emotions and make decisions. His prefrontal cortex, where judgments are formed, is practically asleep at the wheel. At the same time, his limbic system, where raw emotions such as anger are generated, is entering a stage of development in which it goes into hyperdrive.

Brain police.

The limbic system, located deep in the brain's interior, is associated with gut reactions, sparking instant waves of fear at the sight of a large snake or elation at a high SAT score. In adults, such emotional responses are modulated by the prefrontal cortex, the part of the brain that lies just behind the forehead and that acts as a sort of mental traffic cop, keeping tabs on many other parts of the brain, including the limbic system.

Indeed, the brain works something like a loosely organized team, with various parts carrying out different tasks and more or less cooperating with one another. The prefrontal cortex, says Karl Pribram, director of the Center for Brain Research and Informational Sciences at Radford University in Virginia, is in charge of "executive functions."

These include the brain's ability to handle ambiguous information and make decisions, to coordinate signals in different regions of the brain, and to tamp down or prolong emotions generated in the limbic system. In an adult, for instance, an overheard insult might arouse a murderous rage, until the prefrontal cortex figures out that the comment was meant for somebody else and tells the limbic system to pipe down. As Pribram puts it, "The prefrontal cortex is the seat of civilization."

Something very different happens in teenagers, according to Deborah Yurgelun-Todd, a neuropsychologist at McLean Hospital in Belmont, Mass. In recent experiments, Yurgelun-Todd and graduate student Abigail Baird showed adults and teenagers photographs of people's faces contorted in fear. When the researcher asked her subjects to identify the emotion being expressed, all of the adults got it right. Many of the teens, however, were unable to correctly identify the expression.

Then the researchers used functional magnetic resonance imaging, a technology that takes a picture of brain activity every three seconds or so in order to see which parts are being used during processing. Adult brains, the scientists discovered, light up in both the limbic areas and the prefrontal cortex when looking at expressions of fright. In teenagers, however, the prefrontal cortex was almost dark while the limbic system lit up.

These results suggest to Yurgelun-Todd that kids may not be as good as we think they are at interpreting facial expressions, in part because the prefrontal cortex is not yet lending the limbic system a hand. Teenagers are not adept readers of social signals, such as facial expressions, even if they seem to do nothing but socialize. "You have to actually learn how to read emotions," says Yurgelun-Todd. "We may think anger is pretty obvious to our kids, but they may not."

Map makers.

Yurgelun-Todd's research reinforces other new findings suggesting that the average teenager's prefrontal cortex isn't ready to take on the role of brain CEO. At NIMH, Giedd and colleagues are using another type of MRI, which captures brain structure rather than activity, to chart for the first time normal brain development from childhood through adolescence.

Since 1991, Giedd and his colleagues have mapped the brains of nearly 1,000 healthy children and adolescents ranging in age from 3 to 18. Each child must lie inside a claustrophobically narrow tube surrounded by the giant, humming machine, holding perfectly still for 10 minutes at a stretch while a computerized brain image is built.

The researchers expected to find that after puberty, the brain looks like an adult's. Instead, they found that the prefrontal cortex undergoes a growth spurt at around age 9 or 10, when neurons begin sprouting new connections, or synapses. Most of these connections subsequently die off, starting at about age 12, in a process called pruning--a sort of "use it or lose it" system for ensuring that the brain nourishes only the neurons and synapses that are useful. Pruning, which occurs in different parts of the brain at different times, also appears to allow the brain to think more efficiently.

Until the prefrontal cortex has been pruned, most young teenagers don't yet have all the brain power they need to make good judgments.

Researchers suspect that the excess of synapses means the young

adolescent mind can't easily keep track of multiple thoughts, and it can't gain instant access to critical memories and emotions that allow grown-ups to make judicious decisions.

"Good judgment is learned, but you can't learn it if you don't have the necessary hardware," says Yurgelun-Todd. An unfinished prefrontal cortex also means that young teenagers may also have trouble organizing several tasks, deciding, for example, which to do first: call a friend, wash the dishes, or read the book for a report that's due in the morning.

The teenage tendency to leap before looking is compounded by the fact that adolescence is a time for seeking out new experiences, including some that are dangerous. "I think all people do stupid things sometimes. It just seems like teenagers do it more often," says Rachael Fisher, an 18-year-old senior from Lakewood, Colo. That's an understatement. Driving without a seat belt, getting tattooed, smoking cigarettes, shoplifting--the list of foolish things kids do is longer than most parents really want to know.

Parents can relax a little, says Lynn Ponton, a child psychiatrist at the University of California-San Francisco and author of *The Romance of Risk*. "Risk taking is normal." But not all of it, she adds, is safe. Other research suggests that about 60 percent of a teenager's tendency to act impulsively and misjudge potential danger is genetic, a trait that is shared with other family members and is probably the result of differences in brain chemicals among individuals.

Mental mosh pit.

Researchers also think that new experiences, especially those with a frisson of danger or the thrill of the new, tap into a teenager's so-called reward system, a set of neurons that link emotional centers to many other parts of the brain and that can produce feelings of intense pleasure. This is the same set of neurons affected by certain illicit drugs, such as cocaine, that release dopamine, one of the brain chemicals, or neurotransmitters, that are responsible for arousal and motivation.

Marvin Zuckerman, a professor of psychology at the University of Delaware, and others suspect that thrills--like sneaking out at night or jumping into the mosh pit at a heavy-metal concert--stimulate the teenage brain's dopamine system, for reasons that are not yet fully understood. The result, however, is clear: Teenagers are far more interested in novelty than children or adults are, probably because it makes them feel good. Other research has shown that at the same time, levels of another

neurotransmitter, serotonin, appear to decline temporarily in most adolescents, making them more likely to act impulsively.

Added to this brew of neurotransmitters are the sex hormones, which not only turn on an interest in sex but also change the brain's architecture. Giedd and his colleagues recently reported for the first time that, in both sexes, surges of testosterone at puberty swell the amygdala, an almond-shaped part of the limbic system that generates feelings of fear and anger. (Girls' bodies make testosterone by breaking down estrogen, while boys' bodies transform testosterone into an estrogen-like hormone called estradiol.) This blossoming of the amygdala is especially pronounced in boys, but it may account for the rise in aggressiveness and irritability seen in both sexes at adolescence. Increased levels of estrogen at puberty are responsible for the sudden growth of the hippocampus, the part of the brain that processes memory. The larger the hippocampus, the better the memory, at least in animals. The hippocampus in girls grows proportionally larger than it does in boys, a finding that may help explain why women are better than men are at remembering complex social relationships and are likely to suffer less from the memory loss that accompanies Alzheimer's.

Estrogen and testosterone may not alter the brain at puberty so much as flip neurological switches, which were set by hormonal levels while a child was still in his mother's womb. Once flipped, these switches have a profound effect on a teenager's sex drive and moodiness.

Shifts in prenatal hormones also affect mental skills in ways that may not become apparent until later in life. Testosterone, for example, appears to shape centers in the brain that process spatial information. Evidence for this comes from a study of girls with congenital adrenal hyperplasia, or CAH, a condition that causes their adrenal glands to pump out excess androgen, a testosterone-like hormone, during prenatal development. Once the girls are born, they are given cortisone, to keep the body from producing too much androgen.

Their brains, however, have already been molded. Sheri Berenbaum, a psychologist at Southern Illinois University medical school, and others have found that as teenagers, girls with CAH report they are more aggressive than their sisters, and they have better spatial skills--the ability to rotate an object in their minds, for instance, or to imagine how pieces of a shape fit together. They are also more interested than their sisters in becoming engineers and pilots, traditionally masculine professions. But researchers don't yet know precisely how testosterone molds the brain's

ability to imagine all the facets of an object, or why it would make girls (or boys, for that matter) want to become engineers.

One of the last steps in making an adult brain is the coating of nerves in white matter, fatty cells that spiral around the shaft of nerves like vines around a tree. The white matter, also known as myelin, acts like the insulation on an electric cord, allowing electrical impulses to travel down a nerve faster and more efficiently. This is one reason a toddler is less coordinated than a 10-year-old. It now appears that many of the nerves connecting different processing centers in the brain don't finish myelinating until the early 20s.

Some of the nerves that become sheathed during adolescence connect areas of the brain that regulate emotion, judgment, and impulse control. Francine Benes, a neuroscientist at McLean Hospital, says that these nerves myelinate in girls earlier than in boys, which may help explain why teenage girls seem more emotionally mature than boys, whose myelin levels may not equal girls' until age 30.

The myelination process also has been implicated in schizophrenia, which often becomes apparent in late adolescence. Benes believes the faster transmissions overload defective nerves in schizophrenics. "If the circuit starts to have too much information coming in too rapidly, it may become overwhelmed."

Laying foundations.

Researchers feel they have only begun to probe the workings of the adolescent brain, but their findings already offer some new ways for parents to deal with teenagers. During adolescence, many higher mental skills will become automatic, just the way playing tennis and driving do. Kids who exercise their brains, in effect, by learning to marshal their thoughts, to measure their impulses, and to understand abstract concepts, are laying the neural foundations that will serve them for the rest of their lives.

"This argues for doing a lot of things as a teenager," says the NIMH's Giedd. "You are hard-wiring your brain in adolescence. Do you want to hard-wire it for sports and playing music and doing mathematics--or for lying on the couch in front of the television?" This hard-wiring also provides yet another reason for teens not to take drugs or alcohol, because they may permanently alter the balance of chemicals in their brains.

Parents can take comfort in knowing that searching for new experiences is a normal part of growing up. The trick, say experts, is helping kids find healthy sources of stimulation. For one child, being in the school play or volunteering in the community may provide plenty of excitement. For another, it could take hang-gliding lessons. The problem, of course, is that safe risks are not always available to the kids who need them. "Middle-class kids can go skiing and scuba diving," says the University of Delaware's Zuckerman. "But for many kids, there's just crime, sex, drugs, and rock-and-roll."

The best news for parents is that the vast majority of kids will make it through adolescence with few permanent scars, except perhaps the occasional hole through a bellybutton. New research shows that most children emerge from adolescence physically and emotionally intact--although their parents will probably never be the same. Mary Scott, 48, of Port Jefferson, N.Y., is a veteran of teenage wars: She's the mother of two adolescents and a 22-year-old. "Occasionally they do things that are so incredibly selfish, it's unbelievable," she says. On the other hand, Scott adds, "If they didn't drive you crazy, they'd never leave [the nest]." Maybe adolescence is nature's way of forcing children to grow up.