The years between childhood and adulthood are a stage of life that brings out strong feelings in just about everyone. For the young person ready to dash full speed ahead into adolescence, as well as for the adult getting ready to see adolescence from the other side as a parent, the prospect stirs up a mixture of impatience, anxiety, excitement, and just plain curiosity. The next several years will include many “firsts”: receiving a driver’s license (or sitting in the passenger seat while your baby daughter drives); landing a real job (or seeing your self-effacing son brandish his first paycheck); suddenly being (or welcoming) the newest participant in dinner-table discussions of world politics; experiencing (or reliving) the terrors and the bliss of a first love. Perhaps no amount of reading can prepare adolescents and their families for the explosive growth ahead, but some understanding of the brain in adolescence can offer a helpful perspective.

Research into adolescent brain development now makes use of such techniques as brain imaging and very precise hormonal probes, plus new methods to make observations and analyze information in ways that are sensitive to the context in which the information is collected. Sophisticated, long-term investigation promises a wealth of findings yet to come, but today’s scientific understanding already provides the outlines of the picture.

**Sorting Out Adolescence from Puberty**

What can a 20-year-old brain do that a 14-year-old brain cannot, and what takes place in between those ages to make the difference? Although the answer to this basic question is still incomplete, one point that has been firmly established in recent years is that, despite our inclination to think of adolescence and puberty as a single stage of development, each has its own timetable and its own distinct effects on mind and body.

The series of biological changes called puberty is concerned with ushering in our reproductive ability and begins well before the teenage years, often as early as age 8 or 10. This is when the adrenal glands (best known for producing the heartracing, artery-tightening hormone adrenaline) reach maturity and sharply increase their production of the hormone dehydroepiandrosterone (DHEA), which is geared toward sexual development. Meanwhile, the hypothalamus, a small but powerful structure that regulates heart rate, appetite, and other vital systems, sends a chemical message in the form of gonadotropin-releasing hormone to the pituitary gland, just below it. The pituitary gland then sends the hormones known as gonadotropins to the gonads (the ovaries or testes). Interestingly, the same chemical message produces parallel results in the two sexes: in the female, egg cells begin to develop into fertilizable eggs and the ovaries begin to produce estrogen, while in the male, the testes begin to produce both sperm and testosterone. The rising levels of estrogen or testosterone bring about some of the more noticeable changes in an adolescent’s body: breast development, pubic hair, and a fuller figure in females; more muscular development, voice change, pubic hair, and, finally, facial hair in males.

In contrast to puberty, the process of adolescence is aimed toward mental and emotional adulthood, and it is all but invisible because it takes place entirely within the brain. Inside that confined space, a great transformation is under
An adolescent who may outwardly appear disorganized and inconsistent is actually undergoing important physical changes within the skull, all taking place in precise coordination throughout billions of brain cells. Biological changes in the brain (which we will discuss in more detail below) lay the groundwork for new modes of thinking and behaving, at the same time the young person is striving in school and outside of it to master more abstract concepts, more nuanced explanations, and a greater perspective on life in general.

**CHANGES IN SLEEP**

The physiological changes of puberty produce powerful effects on the brain. One of the most striking examples appears in patterns of sleep. The bedtime established in childhood no longer seems late enough; most adolescents begin to move it along by a good hour or more, even if this makes it more difficult to wake up at the usual time in the morning. For a long time, experts thought this shift was due entirely to peer pressure or to the typical adolescent’s expanding social life, but most now agree that some biological factor plays a role here as well. The identity of this factor is still in question; so far, the best evidence points to a time shift in the body’s daily production of melatonin, a hormone associated with the onset of sleepiness.

Keeping later hours on weekends may not pose a serious problem, but during the week a teenager pays a heavy price. If school hours require rising as early as ever, the upshot is that the teenager will be sleep deprived by at least an hour a day, five days in a row, which can add up to a sleep deficit that drags along from one week to the next. The result, apart from the teenager’s feeling tired and perhaps emotionally on edge, is an eroded ability to learn and to remember. A great deal of research now suggests that sleep plays an important role in the brain’s consolidation of long-term memory; thus, a chronic sleep deficit during these later formative years may take a toll that goes beyond mere weariness. In addition, studies suggest that sleep deprivation raises the risk of drug or alcohol use, perhaps by hobbling reasoning and judgment.

**Behind the Scenes in the Adolescent Brain**

A large part of adolescent development takes place in the frontal lobes, which house an incredible number of faculties that we use many times each day. Here are the brain sites that enable us to make sense of the floods of information constantly being gathered by our five senses; to know when we are experiencing an emotion, and even to think about it while we feel it; to understand and keep track of the passage of time; and to hold a thought or object briefly in the forefront of our mind while we proceed with another thought (an ability known as working memory). According to a recent animal study of frontal lobe development, several different “transporter” molecules, which help the neurons to take in neurotransmitter molecules and break them down for reuse, either increase in density during adolescence or reach a plateau, which in turn alters some signaling pathways and stabilizes others. Partly from refinements in the signal circuits of the frontal lobes and partly through accumulated experience, adolescence gradually brings greater independence along with new capacities to plan, to consider the possible consequences of an action, and to take responsibility for the conduct of one’s life.

Not surprisingly for a major executive center, the frontal lobes must reorganize to meet new demands, and they do so at more than one level in the years leading up to adulthood. One of the most significant changes (which actually continues well into adulthood) is a major increase in the myelination, or insulation, of the nerve fibers going both into and out of the frontal lobes. Greater insulation here means faster signaling, and perhaps more highly branched signaling pathways, between frontal lobe neurons and those in any distant region of the brain. This is a development
that we can understand on an everyday level. Clearly, the more information the executive center can gather in various modes—visual signals, the emphatic tone of someone’s voice, the emotions of the moment—the more nuanced and appropriate the brain’s responses can be.

At a day-to-day level, adolescents encounter increasing demands on their attention. For starters, entering middle school or high school means a lot more to keep track of. Instead of being with one teacher in one classroom all day, students move among a half-dozen different classrooms, with a homeroom somewhere else and a locker at yet another place. And, typically today, it quickly becomes necessary to juggle various homework assignments and projects and to balance them against sports or after-school activities, paid or volunteer work, and an ever more complicated social life. Is it any wonder that researchers, psychologists, and sociologists alike are becoming concerned about the long-term effects of these very crowded schedules on the young, developing brain? Some experts warn that our society may be overencouraging the development of quick responses and mental multitasking in young people, at the expense of equally valuable life skills: planning, thinking things through, and predicting the consequences of actions.

Whether such trade-offs are taking place on a large scale, and how they may affect the brain and behavior throughout adulthood, will become clear only with studies that can follow young people for a decade or more. Meanwhile, today’s adolescents have their hands full trying to manage conflicting demands on their time, energy, and attention. Which would be a better use of time—attending an extra soccer practice in order to start in next week’s game or finishing a history project now to avoid having to work on it over the weekend? Is being in charge of your family’s recycling as worthwhile as volunteering two hours a week at a local soup kitchen? Young adolescents may resent or shy away from making such decisions, aware only of the appeal of each option. This behavior, although frustrating to others, is not really surprising, since their prefrontal cortex (the furthest-front portion of the brain) is not yet mature enough to offer much help either in setting priorities or in weighing the likelihood that it may not be possible to do everything at once.

Fortunately, a brain development that begins in the midteens, just in time to help with such difficulties, is the maturing of the anterior cingulate gyrus, a ridge in the middle of the frontal lobes that controls our ability to maintain attention, or to shift attention from one object to another. A young person may gradually notice an ability to focus thoughts more sharply than before or keep his or her mind on topics for longer periods. Others will also be struck with this development as they hear the adolescent delve into more complex ways of thinking. In making plans, for example, adolescence means getting better at allowing for the unexpected (“But if I’m not going to be there by 12, I’ll call you”), and in conflicts, particularly where a friend is involved, it means considering a situation from more than one perspective (“I know he’s angry, but he shouldn’t take it out on his girlfriend”).

Two brain structures involved in feeling and thinking—the amygdala, which plays an important role in the processing of emotions, and the hippocampus, crucial for the formation of memories—increase in volume up to age 18, adding many new synapses to enhance cell-to-cell communication. Intriguingly, the amygdala grows proportionately larger in males, which may explain why young men often seem to gain an extra measure of irritability and aggressiveness in early adolescence (although young women can certainly show these traits as well). In contrast, the hippocampus increases proportionately more in females, perhaps laying the groundwork for their special adeptness at remembering complex social relationships, an ability that may have helped to promote the survival of our human ancestors.
Meanwhile, the corpus callosum, the thick bundle of nerve fibers best known for transporting signals between the left and right hemispheres, also undergoes physical change, increasing in size up to about age 18. The nerve fibers take on more myelin, a fatty white matter that acts as insulation, so that the speed of signaling between the hemispheres and among many sites within each region increases many times. In the hemispheres themselves, a wave of growth adds more nerve fibers to the “association” cortex, where the brain translates the data from our five senses into mental perceptions, and to the regions concerned with language. Taken together, these changes both enable and support an adolescent’s sense of experiencing life with greater intensity, while he or she reaches for new language with which to convey this sense.

Contrary to what we’d expect, some of our mental abilities develop in adolescence not by the adding of new synapses, but by means of the process scientists have labeled pruning—eliminating synapses that are weak or underused. A study of pubertal monkeys, aged about 15 to 20 months, observed a significant loss of one particular type of synapse in the prefrontal cortex. These synapses, which allow rapid communication with nearby cells but not with distant ones, are distributed in a pattern that looks like stripes, and the authors of the study suggest that the narrowing of these stripes is responsible for the notable improvement in short-term, or working, memory that usually takes place by the end of adolescence.

Pubertal hormones appear to play a role in synaptic pruning. The general effect is to refine and reinforce, rather than replace, the brain’s signal pathways, through which the nerve cells exchange chemical and electrical messages. When this intricate process unfolds in normal fashion, the rewards are considerable. A young person will have gained a new capacity for abstract thinking, the ability not only to dream but also to plan, and the consolidation of a core identity, which in turn opens the way for deeper love relationships and for enduring satisfaction in work, friendships, and many other areas of life.

If young teenagers sometimes appear to be thrown off course by their hearts and their hormones, they have good reason. Because puberty is usually well under way, urging young people toward romantic and sexual relationships several years before the brain developments of adolescence begin to take root, people at this age lack the moderating influence of the frontal lobes that they will later come to rely on. With little impulse control, critical judgment, or a steady self-image, it is no wonder that young loves or young flings seem to blossom so suddenly and fade so quickly. To add to the confusion, puberty, the biological stage of development, comes to some young people earlier than to their peers, creating an uncomfortable “maturity gap.” Parents may see a youngster’s physical and emotional changes outstripping mental development, which runs on a timeline more closely linked to age or experience. Young people going through puberty early may spend years moving about in the adolescent world with a sexually mature body and hormonally activated brain, but still lacking the mental skills to meet adult-level challenges such as defusing anger and hostility (in themselves or in others), foreseeing the consequences of their actions, or delaying immediate gratification for the sake of a long-term goal. To a lesser extent, a feeling of being out of phase—with body, brain, and social self all at odds with one another—is a feature of adolescence for almost everyone.

Having both one’s physical and mental self in flux is what makes puberty and adolescence such a unique stage of life. These years have their perils, but they also bring great opportunities to explore, to widen horizons, and to start taking charge of one’s own future.
The Real Role of Hormones

If a teenager is moody, goofy, or infatuated, people often attribute that behavior to hormones. It is important to keep in mind, though, that hormones circulate in our bloodstream not just during adolescence but throughout our lives, and they serve many purposes beyond those of sexuality and reproduction. For example, every evening a gradual rise in the hormone melatonin entices us to sleep; in the morning, peak levels of the hormone cortisol help get us up and moving. Our weight and energy levels, along with fat storage, are subject to fine-tuning by a hormone known as leptin.

In fact, a rise in leptin is one of the hallmarks of puberty for both sexes. But whereas in girls this rise is dramatic and sustained, bringing along with it an increase in body fat, in boys the increase in leptin is soon suppressed by the much greater production of testosterone—which in turn brings about the dramatic increase of muscle mass often seen in boys during puberty.

At the cerebral level, pubertal changes in hormones represent a set of new challenges to a brain system that has successfully maintained regular hormone levels for years. The hypothalamus and the pituitary gland, the brain sites that coordinate and oversee hormonal systems, need time to mature and to adjust to new cycles and baselines. With the many interactions and biochemical feedback loops that take shape at this time, the brain’s hormone-regulating system is like a living-room thermostat that has been adjusted to exactly the right temperature and then must suddenly contend with the lighting of a hearty blaze in the fireplace.

Just as males and females differ in the nature of their hormonal shifts and in their age of onset, they are also affected by hormones in different ways. These variations are possible because hormones do their job not by circulating passively in the blood but by binding to specific receptor molecules in various tissues: muscle, skin, fat, larynx, and so on. This is why the same chemical message delivered to receptors in different tissues can produce any number of different but complementary effects, such as the increasing muscle mass and deepening voice of a teenage boy, the filling out of the figure of a teenage girl, and the growth of underarm and pubic hair in both sexes.

Major hormonal shifts can affect the mind as well as body, of course, and in adolescence some of the most familiar effects occur in the realm of mood—witness the stereotype of a teen who’s always bouncing from despair to elation and back again. In a less exaggerated way, almost all adolescents find that their feelings seem to have gained a new intensity and that they change and reverse themselves more often than before. Most evidence from the research attributes this not only to surges in the sex hormones themselves, which can act as mood-altering neurotransmitters in the brain, but also to the strengthening of signal circuits within “emotional” brain sites such as the hippocampus and the amygdala. Within these circuits, the signal receptors themselves respond not to overall levels of hormones, but to changes in levels. During puberty this response becomes more pronounced, owing to an increase in the density of receptors.

Toward the end of puberty, at about the age of 15 or 16, this system comes under the moderating influence of the frontal lobes, as signaling pathways between the two regions take on new layers of myelin to insulate the nerve fibers. With a sharp rise in signaling from the brain’s executive center, adolescents of both sexes begin to gain the ability to moderate the powerful effects of hormones on their emotions and behavior. This crucial development can take years
or even a decade, but the outcome lasts for many decades more. Although we never become fully able to choose and direct our own feelings (and how strange life would be if we could do this!), reaching adulthood brings more expertise in directing one’s own behavior—that is, what we choose to do with our feelings.

The complicated mental and emotional shifts involved in a transition from childhood to maturity usually have a strong impact not only on the adolescent but on those around her or him. While the young person may be most aware of changing feelings and physical states—a greater need for sleep, inability to concentrate, or overriding preoccupation with one idea or project at a time—others in the family are more likely to notice and to be affected by intense and changeable moods, perhaps irritability, and often some withdrawal from family life (with greater attention to social life).

**Healthy Risks**

In the context of adolescence, the term risk all too often has alarming association: unprotected sex, drug use, drinking and driving, and more. But risk isn’t always bad; in fact, human development would be impossible without it. Even our first baby steps came with a strong possibility of bumps and falls, yet we all took that risk willingly. A hallmark of maturity is the ability not to avoid risks but to weigh them carefully and manage them well.

Risk taking is a normal part of adolescence, most researchers agree. According to one school of thought, novel or slightly dangerous experiences stimulate the release of dopamine, bringing great pleasure through the circuits of the brain’s “reward system.” As the chief neurotransmitter in the reward system, dopamine is also responsible for feelings of motivation. But thrill seeking and the love of novelty do not carry equal weight in every teenager—several studies suggest that up to 60 percent of a person’s tendency to act on impulse is inherited in the genes and may therefore exist to a similar degree in other members of a family.

Many of the risks we expect adolescents to take—creating romantic relationships, finding and keeping a responsible job, perhaps traveling far from home for schooling or to live on their own for the first time—obviously are positive, major steps toward independence. At the same time, from the adult perspective, other risks, involving physical recklessness (say, stunt driving) or flouting the law (for example, experimenting with drugs), may appear not only dangerous but foolish. It’s often said that young people embrace this kind of risk because “they think they’re immortal,” or at least immune from the consequences of their actions. But what may really be at work here is a crucial gap between what young people rationally know and what knowledge they use in making decisions—a gap that fills in gradually as they learn more from the outcome of each decision.

**Sports**

For a great many adolescents, of course, the greatest and most widely assorted kinds of thrill seeking are found in sports. Particularly in the early teen years, one or two sports may become the overriding preoccupation and organizing principle of a young person’s life—and for many good reasons. Team sports such as football and soccer, and even relatively solitary sports such as tennis and cross-country, offer the satisfaction of both physical challenge and mental skill building, all with a built-in social network and a demanding yet sympathetic mentor or two. Persistent effort is rewarded, thus building up motivation (via the dopamine-based reward system discussed above), which in turn promotes more effort, and so on, in a gratifying and healthy cycle. There is even evidence to suggest that participating in sports may help reduce other kinds of risk taking: for example, a study of female adolescents found
that fewer than one fourth (21 percent) of those who took part in sports were sexually active, as compared with half (50 percent) of those with no athletic activities. However, very intense athletic involvement carries its own risks: another study showed the likelihood of eating disorders increasing along with the level of competition in a given sport.

**Unhealthy Risks**

Risk taking in itself is normal and even necessary for learning to live in the world, but it becomes a problem when carried out in excess, or when it persists in the face of clear warnings about significant, needless danger. Some experts in this area point out that adolescents are most prone to risky behavior in situations presenting new, unexpected challenges—not because of some weak or trouble-seeking character, but simply because they are inexperienced. A desire to experience something new doesn’t necessarily guarantee that we will know how to handle it. We all understand the dangers of, say, reckless driving, but young people may be less adept at keeping those rather impersonal, statistical warnings in mind when they suddenly have to make a real live decision with friends and peers looking on.

This is one reason that practice with risk-carrying situations, especially talking them over beforehand with people an adolescent trusts, can be very helpful. Forethought and discussion also put decisions into better context, enabling a teenager to take into account the thoughts of people close to them but detached from the immediate situation. The National Longitudinal Study on Adolescent Health, which surveyed more than 12,000 high school students throughout the country, has noted that feelings of “connectedness” (feeling close to people at school, fairly treated by teachers, and loved and wanted at home) helped significantly to lower an individual’s likelihood of emotional distress, early sexual activity, substance abuse, violence, and suicide.

**Brain Trauma**

Traumatic injury to the brain is a disorder of major significance to public health, according to the National Institutes of Health, and among teenagers a leading cause of death. Roughly twice as common in males as in females, brain trauma most commonly results from car, motorcycle, and other vehicular accidents; falls; acts of violence; and even sports injuries. Partly because adolescents are the most drawn to risk and partly because they have not yet developed the multiprocessing skills needed to judge risks accurately, the age group from 15 to 24 suffers the highest incidence of brain trauma. Depending on which regions of the brain are injured, a victim may lose physical, emotional, or mental functioning, or perhaps only a very specific faculty such as short-term memory or the ability to recognize faces—but the impact on quality of life may be terrible nevertheless. While it isn’t practical to ask anyone to avoid all activities that carry a risk of brain trauma, it is possible to cut down on risk with some simple protective measures, such as not using a handheld cell phone while driving, driving more slowly in bad weather, and wearing a helmet when bicycling to shield the all-important frontal lobes.

**Substance Abuse**

When it comes to unhealthy substances, it is common nowadays for teenagers to experiment with tobacco, drugs, and alcohol—that is, to try them a few times or on an occasional basis. This certainly does not mean that those who abstain aren’t normal; rather, it suggests they may have a more advanced ability than their peers to weigh nonsimple risks, in which negative consequences are unlikely but could be very serious.
Rarely does mild experimentation bring lasting harm; the greater risk, of course, is that it may open the door to long-term use or even to addiction. In such cases, lifelong well-being is on the line—and there is simply no way to know whether the odds will be on the experimenter's side when exposed to this possibility. Fortunately for young people who do become ensnared, alcoholism and drug abuse are no longer considered simply failures of willpower. Extensive research has established that a behavior pattern of acting on impulse, carrying out aggressive urges, and being attracted to danger—including the dangers of substance abuse—has its roots in both biology and psychology. An old nature-nurture debate over whether these tendencies are caused by an individual's genes or childhood environment has given way to the more fruitful question of how a gene-based "predisposition" may be reinforced or inhibited by the individual's environment.

Everyone is familiar with the list of grim health effects that can emerge after years of smoking, ranging from a decrease in the amount of oxygen available to brain cells to an increased risk of lung, prostate, and cervical cancer. What many people may not know, however, is that using tobacco while still in one's teens makes the risk of tobacco dependence even more dangerous. Because the brain in adolescence is so prolific at producing new synaptic connections and so keen at pruning away unused synapses while strengthening those that undergo intense use, addictions that develop at this time in life are much harder to break than those acquired later.

Substances known as recreational drugs have acquired that name because they serve no medical purpose. But that doesn't mean they are harmless—on the contrary, they carry serious risks in both the short term and the long term. To take just one class of these drugs as an example, amphetamines and methamphetamines distort the brain's reward pathway and interfere with everyday living. Users can very quickly become dependent on them for short-lived feelings of boundless energy and euphoria, although these are often followed by severe anxiety, paranoia, or depression. The most recent form of methamphetamine, dubbed Ecstasy, is also one of the most dangerous: regular use of Ecstasy can interfere with mental abilities and with memory for new information, impulse control, and sleep—quite apart from its association with seizures, irregular heartbeat, and liver damage. Some research even suggests that using Ecstasy repeatedly can cause brain damage, particularly to neurons that produce or use the neurotransmitter serotonin. Given the key role of serotonin in the regulation of mood, this damage may gradually bring on a full-fledged mental illness such as major depression.

The problems of alcohol have long been with us, of course, and the fact that drinking alcohol is legal (at age 21) offers a rationale for people who wish to turn a blind eye to its dangers. Yet the evidence of danger is all too clear. Who by now has not heard the sobering statistics on the numerous accidents and acts of violence associated with alcohol, or seen billboards showing the bright faces of young people whose lives were cut short by drunken driving?

In addition, research suggests that adolescents, whose brains have not yet reached their full development, are more vulnerable than adults to alcohol's ill effects. If you have a family history of alcoholism, and therefore a greater risk of developing alcoholism yourself, you may show a high tolerance for alcohol; people will say you "hold your liquor well." The inconvenient truth is that even before you begin to feel drunk, you may have lost a crucial edge in your working memory, your reflexes, and even—most important of all—your judgment. But by far the greatest danger for adolescent drinkers is that they may pave the way for long-term alcohol abuse. And this danger can become real very quickly: whereas an adult who drinks heavily may take anywhere from 5 to 15 years to become fully dependent on alcohol, his or her adolescent drinking buddy may reach this point in less than 18 months.
Kaleidoscope of Changes

Common sense tells us that periods of major development, like that of the brain in adolescence, must include a certain amount of disruption and inconsistency. For this reason, “normal” adolescence is easier to recognize by its successful outcome than by any of the ups and downs of a few days or a few weeks.

The many different societies of the world define adolescence in their own way: some as the beginning of adult life, others as a distinct age that bridges childhood and adulthood. But whether a society marks this stage of life with an arranged marriage, training as a warrior, or the awarding of a driver’s license, the message is that the young person will now take on more weighty responsibilities along with greater independence. The shifting expectations of people surrounding a new adolescent will create some of the frustrating constraints, as well as many of the most exciting opportunities, that await him or her in the next several years.

All the restructuring and rewiring in the brain that has been discussed in this chapter has one essential purpose: to provide the physical basis for the remarkable mental growth that is the work of adolescence. Childhood’s “windows” of optimal time for certain kinds of learning (foreign languages, superior athletic or musical skills) have been left behind, but the windows for other, more far-reaching kinds of learning now appear. By late adolescence the brain has achieved the ability to sustain attention but also to manage several demands at once; to experience all the physical impulses and drives of an adult but also to decide consciously when to act on them; to think more precisely but also more profoundly. And the best is yet to come. Capable as the brain has now become, it will continue to grow and develop for many years more.

About Sandra J. Ackerman

Sandra J. Ackerman is the author of Discovering the Brain and a contributing author of The Dana Guide to Brain Health. She has published numerous articles and columns on a wide range of topics in brain research, medicine, health, and human evolution, and in 2001 received a Rosalynn Carter Fellowship in Mental Health Journalism. She lives in Durham, N.C.