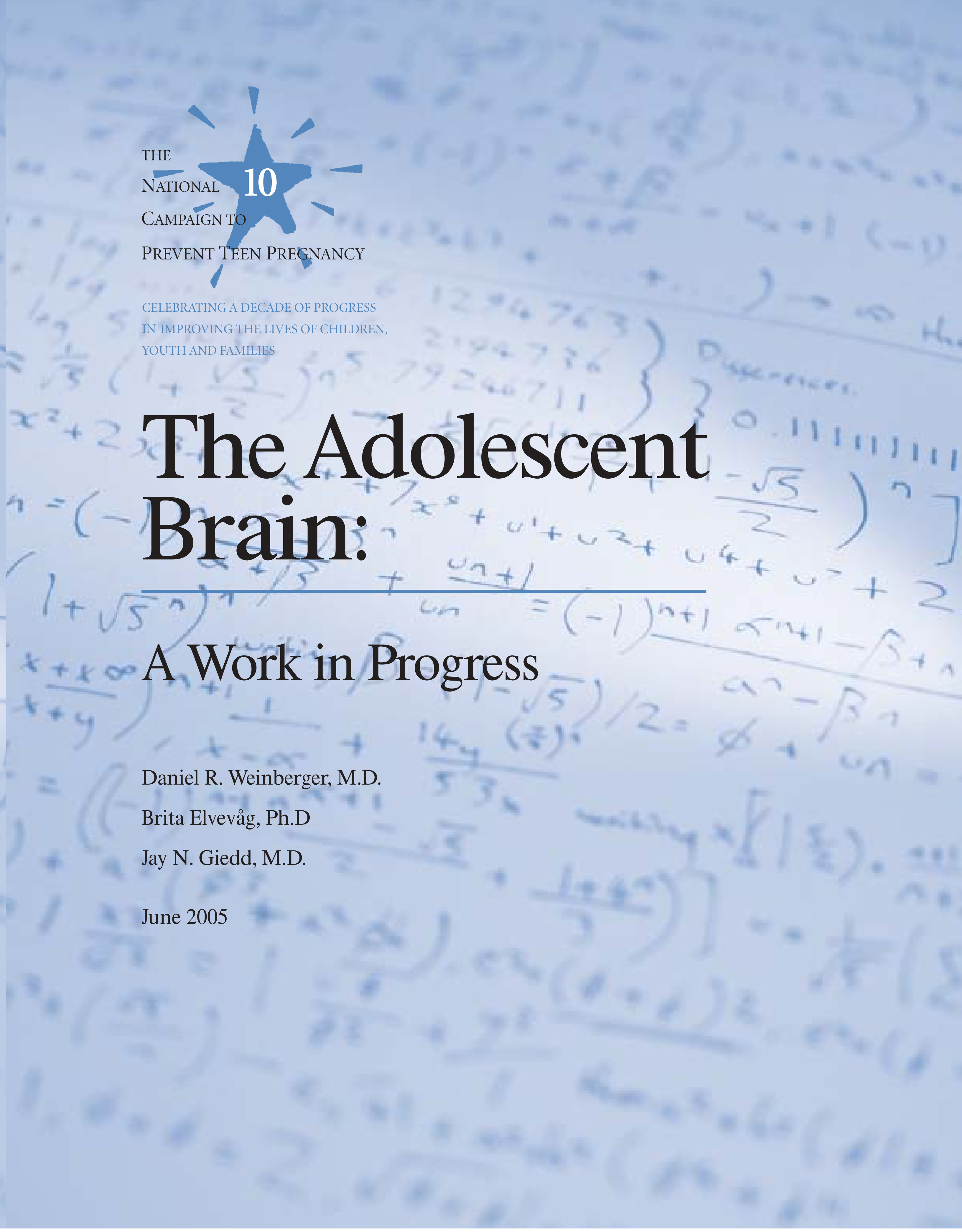

The
National 10
Campaign to
Prevent Teen Pregnancy

CELEBRATING A DECADE OF PROGRESS
IN IMPROVING THE LIVES OF CHILDREN,
YOUTH AND FAMILIES

The Adolescent Brain:

A Work in Progress

Daniel R. Weinberger, M.D.

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June 2005

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Foreword

When the National Campaign first set up shop in the mid-1990s, a serious commitment was made to basing the entire enterprise on science and research. We strongly believed then, and still do, that when an organizations deals with a complicated and controversial issue such as teen pregnancy, a solid grounding in the facts significantly strengthens the overall enterprise. In that spirit, one of the very first advisory groups established by the National Campaign was the Task Force on Effective Programs and Research. To this day, this Task Force remains a critical part of the National Campaign's work, and it was under its auspices that the paper presented here was developed.

Two of the most important tasks that the Research Task Force and the National Campaign have addressed are (1) trying to understand the factors within teens themselves and their broader environment that help to determine teen sexual behavior and pregnancy, and then, based on such insights, (2) outlining approaches to teen pregnancy prevention that are likely to be most effective. This basic line of inquiry has brought us into contact with countless teens and parents, advocates and experts in the field, and people who fund, run, and study intervention programs.

From all these sources and more, the National Campaign and others have developed a list of background and contextual factors that help to explain teen pregnancy in the United States. What is striking about this list—in addition to its sheer length—is that it is almost entirely confined to psychological and social factors as attitudes, feelings, beliefs, couple relationships and communication, family and peer influence, community and school attributes, poverty and ethnicity, the characteristics of medical services and clinics, health insurance status and more. Aside from age of puberty, physiological factors are virtually absent. It is as though there were not one biological factor or insight that might deepen our understanding of teen sexual behavior and pregnancy, or that might help us craft effective interventions.

In truth, this inclination to see teen pregnancy only in psychosocial and contextual terms characterizes much of the field generally. For example, the vast majority of conferences about teen pregnancy that occur around the nation rarely include even one session on biological issues that help in understanding adolescent sexual behavior. By contrast, the field of early child development—the so-called "zero to three" community—now combines intense attention to biological development in the prenatal and infant/toddler stages, along with a continuing focus on such psychological constructs as infant personality and temperament and on the impact of various parenting styles.

The paper presented here, authored by international experts in adolescent brain development Drs. Daniel Weinberger, Jay Giedd, and Brita Elvevåg, begins to fill this gap by making a very simple point: neurological development is an important dimension of overall adolescent development, and our efforts to understand, guide and help teens should be based in part on a deeper appreciation of adolescent neurobiology. Being very careful scientists, the authors do not overstate what is known and they do not move immediately or carelessly into recommendations for policy or practice. But they do ask us to expand our view of teens so that important new research on adolescent brain development will be considered as a relevant factor in understanding adolescent sexual behavior and pregnancy.

When the Campaign first began working with the authors of this paper, the topic of adolescent brain development was still a bit remote—hardly the focus of carpool discussions or office chitchat. But in just a few months, it has made it onto the cover of *Time* magazine, into many newspapers, and into numerous popular articles and books, such at *The Primal Teen: What the New Discoveries About the Teenage Brain Tell Us About Our Kids*, by Barbara Strauch, and *Why Do They Act That Way: A Survival Guide to the Adolescent Brain for You and Your Teen*, by David Walsh; it was also the subject of a PBS *Frontline* special, and New York University recently convened a conference on this complex topic. In fact, with this paper, the Campaign is actually weighing in a bit late on an engaging topic.

Not all of the popular writing and press coverage has been careful and measured, of course, but there does seem to be agreement on a basic point: adolescents are not adults. They are on their way to becoming adults, but they are not fully there (or as this paper's authors say, they are still partly "under construction"). And one aspect of their overall development that is not fully complete—perhaps until the mid 20's—is a stable, solid capacity to make complex judgments, weigh closely competing alternatives in a balanced and careful way, control impulses and take the longer view. An important reason that these so-called "executive functions" are not reliably in full effect in adolescence is that they spring from a particular area of the brain—the prefrontal cortex—which is one of the last areas of the brain to fully mature, as this paper details.

At a minimum, this new field of research suggests that neurobiological factors should be *one part* of the wider universe of factors that are considered when trying to understand teen sexual behavior, decision-making and pregnancy. In addition, these findings are consistent with the view that adolescents may fare best in environments where there is an appropriate degree of structure and guidance within which opportunities for growth and learning exist. Options, yes, but probably limited options along with ample adult involvement. This perspective compliments previous social science research that has repeatedly underscored the pressing need that adolescents as well as children have for close, caring relationships with the adults in their lives.

Interestingly, these new insights into adolescent neurobiology have troubled some people. They worry, for example, that if teens are viewed as less than fully mature neurologically, they will be treated as incompetent or worse, they will be denied opportunities to make autonomous decisions, and/or adults will use this new information to unfairly restrict or control teens. For example, could this research be used to argue that minors should not be able to obtain family planning care without parental consent? Could these new insights into adolescent brain development be used to prevent courts from charging minors as adults in criminal cases?

The Campaign has considered these worries and offers several thoughts. Most fundamentally, we assert that no one should turn away from new research findings just because they might modify our thinking. In addition, the scientists working in this area are the first to be cautious, to note that more research is needed to fully understand adolescent brain development, and to point out that the precise practical applications of these new findings are not yet clear. Moreover, no one is suggesting that young people are incompetent or that they lack capacity for making good decisions. Rather, the message is that teens—however competent—are not adults, and we need to think harder about the nature of this critical life stage. As Jay Giedd himself has said, "Teenagers are capable of enormous intellectual and artistic accomplishments, but the basic part of the brain that gives us strategies and organizing and perhaps warns us of potential consequences is not fully on board yet." (See the PBS *Frontline* program, "Inside the Teenage Brain," www.frontline.org)

The National Campaign expresses warmest thanks to the authors for their diligence, patience, and heroic efforts to explain deeply complex ideas in relatively simple terms. We look forward to following this exciting new area of research and to thinking about its potential application to preventing teen pregnancy.

Sarah S. Brown
Director, National Campaign
to Prevent Teen Pregnancy
May, 2005

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Summary

Neuroscience, the scientific study of the biology of the brain, has made great strides over the past decade in revealing that remarkable changes occur in the brain during the second decade of life. Contrary to long-held ideas that the brain was mostly grown-up—"fully cooked"—by the end of childhood, it is now clear that adolescence is a time of profound brain growth and change. In fact, the brain of an early adolescent in comparison to that of a late adolescent differs measurably in anatomy, biochemistry, and physiology.

Between childhood and adulthood, the brain's "wiring diagram" becomes richer, more complex and more efficient, especially in the brain's frontal lobe, or front outer mantle, which is the seat of such higher order functions as learning and socialization. An important part of the frontal lobes is the prefrontal cortex (PFC), which is often referred to as the "CEO" or executive of the brain and is responsible for such skills as setting priorities, organizing plans and ideas, forming strategies, controlling impulses, and allocating attention. New research suggests that the PFC is one of the last areas of the brain to fully mature.

The brain produces a large number of neural connections just before puberty—connections that diminish in number throughout adolescence through a "use-it-or-lose-it" pruning. Through this process, the brain becomes leaner and more efficient. Like a sophisticated computer, the maturing brain also grows circuits that can perform several tasks simultaneously and with ever-greater efficiency. As circuits mature, they become coated with a layer of a white fatty substance, myelin, which speeds communication, much like the insulation on electric wire.

In addition, cells that use the chemical messenger dopamine—a neurotransmitter that, among other things, increases one's capacity to learn in response to reward—increase the density of their connections with the prefrontal cortex. Dopamine inputs to the prefrontal cortex grow dramatically during adolescence, probably representing one of the neuronal mechanisms that increase the capacity for more mature judgment and impulse control. Indeed, beginning in adolescence, the dopamine reward signal becomes especially important in the prefrontal cortex as ideas, *per se*, become increasingly reinforced and valued.

It is also apparent that regions of the cortex (i.e. the outer mantle layer of the brain) that handle abstract information and that are critical for learning and memory of such concepts as rules, laws, and codes of social conduct seem to become much more likely to share information in a parallel processing fashion as adulthood approaches. This increased information sharing is reflected in the patterns of connections between and among neurons in different regions of the cortex. For example, the branching of neurons in the prefrontal cortex becomes much more complex during adolescence, likely reflecting a more intricate web of information flow. It is as if the cells change their architecture in order to meet the increasingly difficult cognitive and emotional challenges that they are being asked to master. By the end of the twenties, the profile of cell-to-cell contacts reaches an adult pattern and the number of connections reaches a steady state that persists until old age.

Magnetic resonance imaging (MRI) is a medical imaging technique that safely provides exquisitely accurate pictures of the living, growing brain and has helped launch a new era of adolescent neuroscience. MRI studies show clearly that during adolescence, the brain is in a dynamic biologic state and that it exits this period in a different state from which it enters. Although it is not clear exactly what cellular processes account for the ebb and flow of the cortex's volume seen on MRI scans during adolescence, it is clear that changes are occurring. In healthy subjects, the cortical gray matter thickens throughout childhood as the brain cells grow an exuberance of connections to other brain cells—gray matter that is pruned in a back-to-front sequence through the teen years. MRI studies also show an opposite front-to-back wave of increases in white matter through childhood and adolescence. Like Michelangelo starting with a block of granite and eliminating rock to create the masterpiece David, certain connections are strengthened and others eliminated—in essence, brain functions are sculpted to reveal and allow increasing maturity in thought and action.

Scientists do not yet understand all of the forces that guide the building up or pruning down of connections between cells. Both are likely influenced by genetic and environmental factors. The roles of bacteria, viruses, nutrition, education, parenting, school, peers, drugs, video games and many other factors are hotly debated. At present, the scientific jury is still out regarding how much of this process is automatic versus how much is susceptible to manipulation and intervention.

In addition to revealing more about the changing structure of the brain during adolescence, MRI can also be used to see the activity of the brain at work. For example, one key MRI study found that when identifying emotions expressed on faces, teens more often activated their amygdala—the brain area that experiences fear, threat and danger—whereas adults more often activated their prefrontal cortex—the area of the brain linked more to reason and judgment—and performed better on the task. Behaviorally, the adult's responses were more intellectual, the teens' more from the gut. These findings and others suggest that although the plasticity and changeability of the adolescent brain are extremely well suited to meet the demands of teen life, guidance from parents and other adult institutions are essential while decision-making circuitry is being formed.

Impulse control, planning and decision-making are largely frontal cortex functions that are still maturing during adolescence. One way that the functions of the frontal lobes have been understood is by observing changes in the cognitive processes and behavior of adults who have suffered injury to this key area of the brain. For example, adults whose frontal lobes are damaged often tend to be more uninhibited and impulsive. Often unable to suppress irrelevant information, people with this kind of damage are often easily distracted and falter at even the simplest tasks requiring sustained attention and short-term memory. Such observations suggest that one reason adolescents may have difficulty inhibiting inappropriate impulses is that the circuitry needed for such control is not fully mature in early adolescence, thereby making such tasks relatively difficult.

Planning behavior is another case in point. Adults with damage to the prefrontal cortex tend to be inflexible in adapting to the environment. Studies show that the ability to plan improves with age until adulthood, since the process requires a temporary mental workspace—"working memory"—which is still developing throughout adolescence. Similar parallels can be drawn with regard to decision-making. Damage to the lower middle portion of the adult prefrontal cortex appears to impair the ability to imagine the future consequences of actions or to appropriately gauge their emotional significance. One needs to be able to estimate the probabilities of the possible outcomes of actions in order to make appropriate decisions and to appreciate the complex relationships of cause and effect. People with such damage tend to make decisions on the basis of immediate reward. And it has also been learned that teens are prone to certain types of flawed logic or to ignoring cues about how questions are framed in their decision-making. Again, such observations suggest that one reason adolescents may have limited cognitive ability to simultaneously process information about antecedents and outcomes, hold it in working memory, and use it to make decisions is likely traceable, in part, to brain circuitry not fully developed and still under construction, particularly in the prefrontal cortex of the frontal lobes.

In sum, a large and compelling body of scientific research on the neurological development of teens confirms a long-held, common sense view: teenagers are not the same as adults in a variety of key areas such as the ability to make sound judgments when confronted by complex situations, the capacity to control impulses, and the ability to plan effectively. Such limitations reflect, in part, the fact that key areas of the adolescent brain, especially the prefrontal cortex that controls many higher order skills, are not fully mature until the third decade of life. Teens are full of promise, often energetic and caring, capable of making many contributions to their communities, and able to make remarkable spurts in intellectual development and learning. But neurologically, they are not adults. They are, as we say in this paper often, a work in progress.

More research will be needed to fully understand the developing brain, of course, but in the interim, it seems prudent for adults to think carefully about this new evidence regarding teenage brain development. At a minimum, the data suggest that teens need to be surrounded by caring adults and institutions that help them learn specific skills and appropriate adult behavior. But within that fairly obvious suggestion are many more challenging and specific questions. For example, if teens are not the full neurological equivalent of adults, what specific systems and practices will best help them grow and mature in appropriate ways? What opportunities will be most effective in helping them develop the skills of judgment, planning and impulse control? What styles of parenting and teaching can most help teens develop into solid adults? Under what circumstances should teens be allowed to make their own choices among many options, and under what circumstances should directed guidance be offered and options limited? Although such questions are often discussed and debated in schools, families and communities, it is important that the answers arrived at take full note of teens' neurological development. Such biological underpinnings should not be the sole determinant of the answers, but they should clearly inform them.

Key Findings

What we now know

- Neuroscience—the study of brain development—has made great strides over the past decade. This progress is due, in large part, to the development and continued sophistication of magnetic resonance imaging (MRI) that safely provides detailed and accurate pictures of the living, growing brain and of molecular biology, which has allowed for the molecular characterization of changes in brain growth and development in biological model systems.
- Research has now determined that remarkable changes occur in the brain during the second decade of life.
- The understanding that adolescence is a time of profound brain growth and change is contrary to long-held ideas that the brain was mostly fully "formed" by the end of childhood.

How the adolescent brain changes

- Between childhood and adulthood the brain's "wiring diagram" becomes more complex and more efficient, especially in the brain's prefrontal cortex or frontal outer mantle.
- An important part of the front lobes—and one of the last areas of the brain to fully mature—is the prefrontal cortex (PFC). The PFC is responsible for such skills as setting priorities, organizing plans and ideas, forming strategies, controlling impulses, and allocating attention.

How such changes take place

- Like a computer, the maturing brain grows "circuits"—neural connections—that can perform several tasks simultaneously and with ever-greater efficiency.
- Dopamine inputs to the PFC—a chemical messenger critical for focusing attention when necessary to choose between conflicting options—grow dramatically during adolescence.

Why brain changes during adolescence matter

- Impulse control, planning, and decision-making are largely prefrontal cortex functions that are still maturing during adolescence.
- Adult response to stimuli tends to be more intellectual, while teens' is often more "from the gut." This suggests that while the changeability of the adolescent brain is well suited to meet the demands of teen life, guidance from adults are essential while this decision-making circuitry is being formed.
- The ability for the brain to plan, adapt to the social environment, and to imagine possible future consequences of action or to appropriately gauge their emotional significance, is still developing throughout adolescence.
- Brain functions that enhance teens' ability to connect gut feelings with their ability to help retrieve memories, to put situations into context, and to remember past details about a situation that might be important, are also under major construction during adolescence.

Implications

- Neurobiological factors should be one part of a wider universe of factors that are considered when trying to understand teen decision-making and behavior, including pregnancy.
- Teens need to be surrounded by caring parents, adults, and institutions that help them learn specific skills and appropriate adult behavior.
- Teens themselves may be able to shape their own brain development. For example, neuroanatomical evidence suggests that learning and positive experiences help build complex, adaptive brains.
- More research is needed to fully understand the brain development, including the relative influence of genetic and environmental factors and how much of the brain's developing "wiring diagram" process is automatic versus how much is susceptible to manipulation and intervention.

The Adolescent Brain: A Work in Progress

Introduction

Peter Blos, a renowned child psychoanalyst and author, once referred to adolescence as a "crazy time." A recent flurry of popular books echoes this sentiment; note, for example, Michael J. Bradley's *Yes, Your Teen Is Crazy! Loving Your Kid Without Losing Your Mind*, and *Now I Know Why Tigers Eat Their Young: Surviving A New Generation of Teenagers* by Peter Marshall. These titles seem quite overblown, of course, but it is true that the teenage years can be difficult, and many young people struggle with conflicting ideas, confusing emotions, and confounded choices. Adolescence also is a time that challenges one's judgment about taking risks, about making plans, and about balancing short-term rewards with long-term goals. Most people now understand that this stage of life is shaped and affected by such factors as family and friends as well as school and community institutions. But there are also powerful neurological issues at play—factors that this paper describes—which merit greater attention from those who seek a deeper understanding of adolescent development and of the teens we live with.

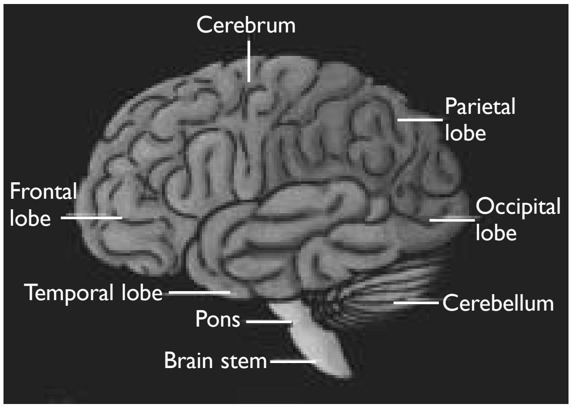
Neuroscience, the scientific study of the biology of the brain, has made great strides over the past decade in revealing that remarkable changes occur in the brain during the second decade of life. Contrary to long-held ideas that the brain was mostly grown-up—"fully cooked"—by the end of childhood, it is now clear that adolescence is a time of profound brain growth and change. In fact, the brain of an early adolescent in comparison to that of a late adolescent differs measurably in anatomy, biochemistry, and physiology.

By the end of adolescence, the human brain, the most complicated three-pound mass of matter in the known universe, contains over 10 billion neurons and another 100 billion support cells. The 10 billion neurons form over 100 trillion connections with each other—more than all of the Internet connections in the world! So how does the teen brain become this massive complex of interconnections and networks?

In the earliest stages of brain development, primarily before birth, there are many more brain cells and connections formed than can possibly survive. A process of competitive elimination, or "pruning," follows this vast overproduction. Those cells and connections that are used survive; those that aren't used wither. This process occurs in all species possessing a central nervous system. In humans, a second bout of overproduction of connections occurs just before puberty, followed by "use-it-or-lose-it" pruning through the teen years, as connections are shaped and refined. These changes have important implications for a teen's ability to become an independent and successful adult, to manage an environment that offers conflicting choices, to understand cause and effect, to plan for the future, and to manage impulses and reject temptations that are not consistent with mature, long-term goals.

In this paper, we summarize recent scientific research about brain development in adolescence. In particular, we emphasize changes in a part of the brain—the prefrontal cortex (PFC) of the frontal lobes—that appear to be especially critical for mature decision-making and impulse control (See Figure 1). Section I addresses changes in the brain during adolescence at the cellular level; Section II also describes adolescent brain development but from the perspective of new techniques now available for studying living brains—i.e., magnetic resonance imaging (MRI). The final section, Section III, summarizes knowledge about how the brain changes described in Sections I and II may affect thinking and behavior.

Figure 1



Section I. Changes in the cellular architecture of the brain in adolescence

The brain is not fully grown at birth, not just in terms of its size, but in terms of the complexity of the networks of nerve cells that determine how it functions (Nowakowski, 1987). The basic functional elements of the brain are nerve cells, or neurons, large assemblies of which join together in information processing neuronal networks. These networks help to turn such sensory information as sights, sounds, smells into complex patterns of behavior. Neuronal networks change as a result of learning, experience and advancing age. The changes that take place over time involve the biology of contacts or connections between neurons, called synapses. While the number of nerve cells may not change much after birth, the richness and complexity of the connections between and among cells do, as does the capacity for these networks to process increasingly complex information. Neuroscience research has established that neuronal connectivity, or synaptic complexity (elaboration of the "wiring diagram"), is the critical developmental change that occurs in the brain after birth.

It has been known for over a century that the gross appearance of the brain changes from birth to young adulthood. In addition to doubling in size, the brain's surface folds become much more complicated. Evidence suggests that this increasingly complex folding may be related to the elaboration of underlying connections among cells. The complexity of the folding patterns becomes increasingly obvious in parts of the brain cortex—the outer mantle—that process cognitive and emotional information (as distinct from parts of the brain responsible for the control of more basic motor and sensory functions)(Chi, Dooling, & Gilles, 1977). In other words, those parts of the brain related to such higher-order functions as learning and socialization appear to show the greatest changes in adolescence. In fact, the evolving pattern of folds and crevices reaches a peak and levels off by the late teens, after which it remains stable throughout adult life.

Connections among neurons have also been studied at much finer levels of resolution.

Anatomists and molecular biologists can count and characterize these connection by using electron microscopes, cell-staining, and molecular labeling techniques to visualize the expression of genes and proteins that identify such synapses. Studies of the brains of humans and of nonhuman primates have revealed dramatic evidence that the number of synapses changes during the first two decades of life (Huttenlocher, 1979). This process is both progressive and regressive. That is, new connections sprout up while others fade away, culminating in a refinement of the architecture of connections and a stabilization of the maturation process by early adult life.

At birth, neurons seem to express an excess of synapses (Okusky & Colonnier, 1982). It is as if each cell sends out antennae in all directions to see what potential contacts are out there. For a synapse to survive, it must encounter a partner, an antenna from another cell, with which to transfer information. Most of the synapses sent out by these young neurons fail to find sustaining partners and they regress. Studies in monkeys show that shortly after birth, there is a net loss of large populations of nonfunctional synapses occurring fairly rapidly during the first six months of the life of a monkey (Rakic et al., 1986). This corresponds to approximately the first 5 years of human life. It has often been stated that this period is a time of extraordinary brain changeability, or "plasticity." This is reflected in the dizzying pace at which the brain acquires new skills, from learning to walk to learning to read. These new skills and abilities are presumably grounded in an elaboration and stabilization of a synaptic architecture constructed as part of the process of learning these new things.

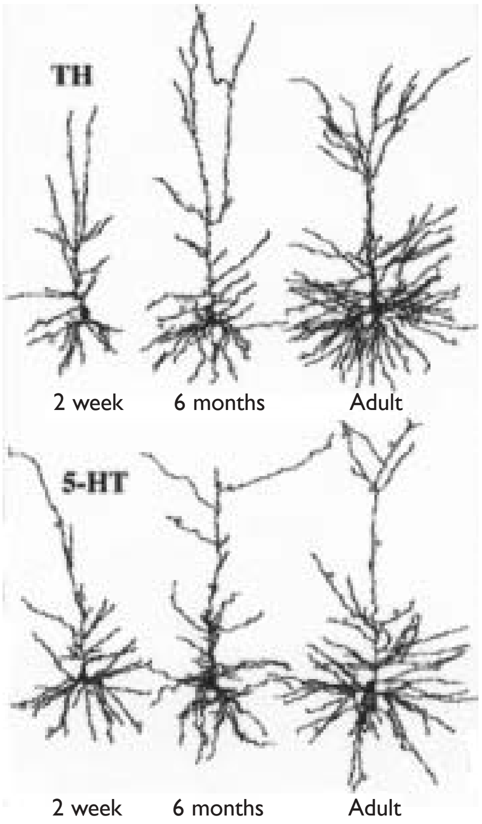
The plasticity of the child's brain is reflected in the fact that damage to it—for example, through a stroke or head injury—can often be compensated for, since so many extra synapses are available to help out and take over for the damaged cells (Kennard, 1936). Later in childhood, after the period of exuberant overproduction of connections, recovery is much more difficult, because the potential for a cell to find an alternative wiring diagram is more limited. For example, if a child's left hemisphere is damaged before age 5 or 6, there is virtually no residual language deficit, as the exuberant connections of the young right hemisphere can take on language capability. After age 7 or so, left hemisphere damage produces language disturbances (aphasia) analogous to that seen with damage to the adult brain (Kotrla & Weinberger, 2000).

When a contact is made between two neurons, each cell sends out proteins that tell the other cell to hold tight and grow a synapse. The proteins secreted by each cell are somewhat different, allowing information to be transferred in both directions, from cell to cell. However, the direction of information transfer is typically weighted in one direction, which is determined by release of a messenger chemical that changes the electrical excitability of the recipient neuron. These messenger chemicals exchanged between neurons are called neurotransmitters. The neuron releasing the neurotransmitter is said to be presynaptic, while the neuron whose excitability is affected by the neurotransmitter is said to be postsynaptic. As the number of functioning synapses grows, the postsynaptic cell grows a more elaborate architecture to receive neurotransmitter signals. The receiving zone of the cell grows synapses primarily on extensions called dendrites, which look somewhat like the roots of a tree. This process is called arborization, from the Latin word *arbor* for tree, and reflects the increased "bushiness" of individual cells as their connections grow like extra branches, twigs, and roots (see Figure 2). The dendrites grow out from the cell body, home to its nucleus (or headquarters) and hub of its DNA—its genetic blueprint. This root structure increases in size and complexity as the synaptic population grows.

Precisely where a synapse sprouts up on this dentritic tree also varies, depending on exactly what information it is meant to convey. All synapses do not transfer the same signals, since each is constructed to recognize a specific neurotransmitter. For example, some synapses transmit excitatory information and use a neurotransmitter called glutamate, which appears to increase the probability that the receiving neuron will fire and send an impulse to another neuron (excessive excitation of

Figure 2

Elaboration of pyramidal cell dendritic arbor and dopamine inputs in postnatal development of the primate prefrontal cortex.



neurons is one mechanism of epileptic seizures). Other synapses, which occur primarily on the shafts of dendrites, are inhibitory and respond to the neurotransmitter gamma amino butyric acid. Activation of these inhibitory synapses decreases the probability that the receiving neuron will discharge (anti-anxiety and anticonvulsant drugs work by enhancing activity of these inhibitory synapses). From birth to early adulthood, most of the pruning, or loss, of synapses involves excitatory synapses (Lidow, Goldman-Rakic, & Rakic, 1991). Thus, the brain by early adulthood appears to have undergone a reorganization of synaptic balance such that, at least in certain circuits, there is much greater weight on the inhibitory side and less weight on the excitatory side.

In addition to the loss of many excitatory synapses, there is also a growth and elaboration of other neuronal connections, especially those that connect regions of the cortex to one another. As the brain matures, the strategies for handling complex environmental information change. The brain stores and processes information in different regions, largely according to the nature of the information—e.g., visual, auditory, and so forth. As the demands for reasoning and for handling increasingly complicated environments increase with maturity, the brain grows more efficient circuits that can process multiple steams of information in parallel, like a sophisticated computer that uses multiple processors. Unlike sequential processing, in which one computation cannot begin until the output from a previous computation is received, parallel processing divides problems into tasks that can be worked on simultaneously. This greatly increases the speed and capacity of problem solving.

Regions of the cortex that handle abstract information and that are critical for learning and memory of such concepts as rules, laws, and codes of social conduct seem to become much more likely to share information in a parallel processing fashion as adulthood approaches. This increased information sharing is reflected in the patterns of connections between and among neurons in different regions of the cortex. For example, the branching of neurons in the prefrontal cortex becomes much more complex during adolescence, likely reflecting a more intricate web of information flow (Lambe, Krimer, & Goldman-Rakic, 2000). It is as if the cells change their architecture in order to meet the increasingly difficult cognitive and emotional challenges that they are being asked to master (see Figure 2 above).

To bring about these architectural changes, cells turn on many genes, which then synthesize many proteins as the brain rises to the maturational challenge (Romanczyk et al., 2002). Genes function in cells not only to convey hereditary information, but also as the master blueprint for guiding the organism's metabolic machinery throughout its life. Genes related to synapse reorganization are especially active in brain cells during adolescence, probably reflecting genetic programs that make early adolescence a time of dramatic synaptic reorganization in the cortex (Webster, Shannon-Weickert, Herman, & Kleinman, 2002). The signals that herald the initiation of these genetic programs are unclear, but hormonal changes and other maturational factors are probably involved. The sex hormones estrogen and testosterone, for example, act by turning genes on and off, so that as hormonal changes occur during puberty, the genetic regulation of cell metabolism also changes.

Another indication of the maturation of connections among areas of the cortex that takes place during adolescence has come from studies of a process that protects nerve fibers and makes them more efficient. The long extensions that allow neurons to span many centimeters from one brain region to another are called axons. These fibers connect the body of the cell—the nucleus with it DNA and the protein synthesis machinery—to the distant terminals where chemical signals are sent via synapses to the dendrites of other cells. Since axons must conduct electrical impulses over relatively long distances, they are wrapped in a fatty chemical coat called myelin, which makes them more efficient conductors, just like the insulation on electrical wires.

Myelin greatly increases the speed at which signals between brain cells can travel—up to 100-fold compared to axons lacking myelin. During childhood and adolescence, the amount of myelin increases throughout the brain. So, during the teen years, not only does the number of connections change, but the connections themselves also become faster.

Different regions of the brain produce these myelin coats at different stages of brain development after birth. It has been known since early in the 20th century, for example, that the age at which brain circuits become covered with myelin corresponds, more or less, to the time at which they become functionally mature and achieve their adult role. Areas of the brain that process complex abstract information—e.g., learning and memory in the service of goal directed behavior—develop these coats relatively late. Parts of the brain involved in such sensory and motor functions as moving the arms and the eyes are fully myelinated by the first few years of life. The cabling of the prefrontal cortex and related regions, however, is not fully myelinated until well into the third decade of life (Yakovlev & LeCours, 1964). As noted in the next section, MRI scans of living brains have revealed various changes in the volume of white matter during adolescence, which is consistent with changes in myelin content.

Certain neurons that provide more general alerting and orienting signals—signals that help focus the activity of information processing networks within the cortex—also become more robust. One set of cells that shows this pattern in the prefrontal cortex is the set that carries the messenger chemical dopamine. This chemical has been found to be critical for focusing attention on environmental stimuli when it is necessary to chose between conflicting options, especially when the goal may not be obvious and choices based on memory, not impulse, are required. Dopamine inputs to the prefrontal cortex grow dramatically during adolescence, probably representing one of the neuronal mechanisms that increase the capacity for more mature judgment and impulse control (Lambe, Krimer, & Goldman-Rakic, 2000). Indeed, beginning in adolescence, the dopamine reward signal becomes especially important in the frontal lobe as ideas, *per se*, become increasingly reinforced and valued. Since learning is based on reward, the adolescent begins to have the ability to follow an idea in pursuit of a goal, rather than to simply act on instinct.

The role of dopamine neuron growth during adolescence may be important not just for increasing the capacity of the brain to learn in response to reward, but it also may have implications for the vulnerability of the brain to certain drugs of abuse. Drugs such as cocaine and amphetamine target dopamine neurons, and damage to these very neurons caused by such drugs might affect adolescent brain development, especially the brain's ability to experience reward and learn from it throughout adult life.

In addition to changes in the wiring of the cerebral cortex, lower centers of the brain also undergo changes in their connection patterns during the second decade of life. Three areas that have been of particular interest in understanding aspects of impulse control and judgment are the hippocampus, the amygdala, and the caudate nucleus. The hippocampus is critical to the formation of new memories, and studies in human brain and in nonhuman primates indicate that changes in the hippocampus's synaptic organization, dopamine wiring, and myelination also occur during adolescence (Benes, 1989). The caudate nucleus is a relay station for information destined for the prefrontal cortex, and seems to be important for learning to make certain behavioral routines more or less automatic. The amygdala processes emotional information, especially the experience of fear, danger and threat in the environment.

Although the intrinsic neuronal architecture of the hippocampus and amygdala appear to mature relatively early in life, the manner in which this circuitry processes environmental stimuli changes in adolescence. The changes reflect, in part, the fact that the prefrontal cortex controls the responses of these lower centers. Changes intrinsic to these structures might also independently contribute to differential responses or influence prefrontal cortex development and adult function. As the prefrontal cortex matures, a stimulus that might earlier have initiated an automatic behavioral routine or a simple emotional arousal comes to be treated with a more reasoned or deliberate response. The prefrontal cortex's control of more automatic response patterns is another manifestation of the reorganization of brain activity that emerges during adolescence.

In sum, many types and levels scientific inquiry have demonstrated the changing organization of the brain during adolescence. At the most basic level, as noted in this section, these changes involve molecular rearrangements that affect how the brain processes information from one cell to another. Around the third decade of life, the profile of cell-to-cell contacts reaches an adult pattern. The net change in the number of synapses tends to level off and reach a steady state that persists until old age. The many molecular changes that occur during adolescence make it clear that—from the perspective of biological maturation at a minimum—the adolescent brain is still a work in progress.

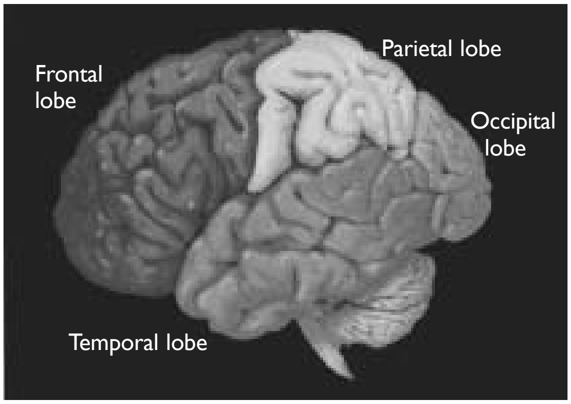
Not surprisingly, these cellular changes are reflected at other levels of the living brain, including its gross structure and function, as revealed by studies using neuroimaging and by studies that assess cognition and behavior. The next two sections summarize the evidence that the adolescent brain undergoes reorganization and maturation at these higher levels as well.

Section II. Changes in the adolescent brain revealed through new neuroimaging techniques

Few parents of a teen would be surprised to hear that there are measurable anatomical differences between teen and adult brains, yet actually characterizing these differences in living people has long eluded science. This is because nature has gone to a great deal of trouble to protect the brain during life. It is wrapped in a tough leathery membrane, surrounded by a protective moat of fluid, and completely encased in bone. This has shielded the brain from falls or attacks from predators, but it has also made it hard to study.

Old ways of looking at the living brain, such as X-rays or CAT scans, use harmful radiation, preventing their use for the study of healthy children. Now, magnetic resonance imaging—MRI—safely provides exquisitely accurate pictures of the living, growing human brain and has helped launch a new era of adolescent neuroscience. The most striking finding from a recent series of MRI studies of teens is the enormous plasticity, or capacity for change, that can be observed in the living brain during this time of life.

As summarized in the previous section, studies had revealed the over-production and selective elimination of cells occurring in the womb—processes that are followed by a winnowing of connections between cells for years after birth. But for some time, the evidence of such changes had depended solely on studies of dead brains and on animal studies. Recent MRI studies, which track brain development by scanning the same individuals at two-year intervals through childhood and adolescence, show clear evidence of expansion and regression of the cerebral cortex in living people (Giedd et al., 1999)—a major step forward. On MRI scans, these changes can be seen as a thickening of the gray matter—cell bodies and dendrites—in the cortex.



MRI studies show clearly that during adolescence, the brain is in a dynamic state and that it exits this period in a different state from which it enters. Although it is not clear exactly what cellular processes account for the ebb and flow of the cortex's volume seen on MRI scans during adolescence, it is clear that changes are occurring. In healthy subjects, the cortical gray matter thickens throughout childhood as the brain cells grow an exuberance of connections to other brain cells.

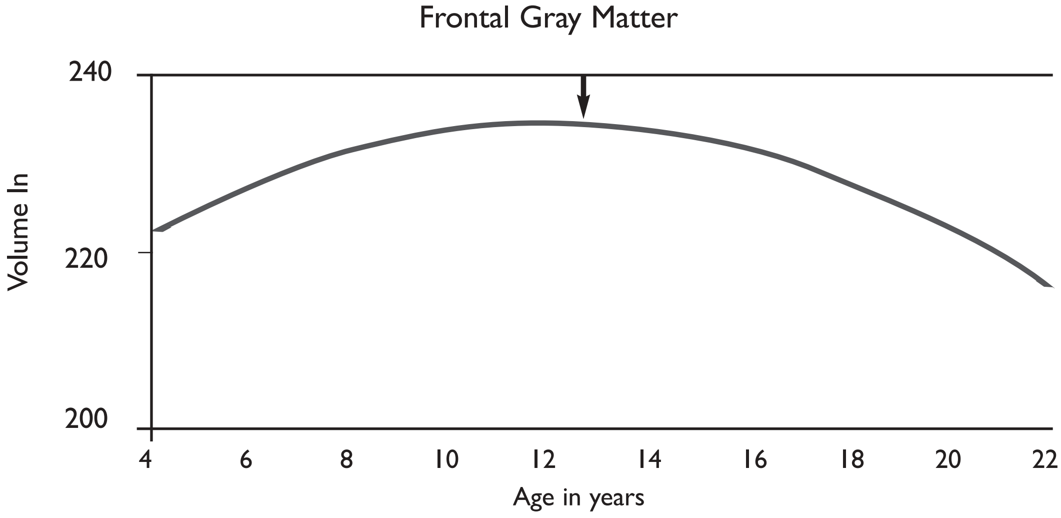
As noted in the previous section, understanding the development of the cortex's frontal lobes—particularly the prefrontal cortex—is particularly important in understanding teen behavior is. As previously noted, the PFC is often referred to as the "CEO" or executive of the brain and is responsible for such skills as setting priorities, organizing plans and ideas, forming strategies, controlling impulses, and allocating attention (see Table 1).

MRI studies show clearly that the level of gray matter in the frontal lobes does not stabilize until well into the third decade of life (Figure 3). While it appears from the figure that the frontal lobe thickness peaks around age 12, this is purely a quantitative value and does not reflect the efficiency of information flow between neurons. It has been assumed by scientists that the shape of the curve in Figure Three reflects a surge of connectional growth in early adolescence in preparation for the final push to adult maturation, followed by a cutting back or "pruning" of inefficient or ineffective connections to achieve maximal efficiency of function. Like Michelangelo starting with a block of granite and eliminating rock to create the masterpiece David, certain connections are strengthened and others eliminated—in essence, brain functions are sculpted to reveal and allow increasing maturity in thought and action.

Table 1: Behavioral and cognitive functions of the prefrontal cortex

- Controlling impulses
- Inhibiting inappropriate behavior
- Initiating appropriate behavior
- Stopping an activity upon completion
- Shifting / adjusting behavior when situations change
- Providing a temporary mental workspace for working memory
- Organizing things
- Forming strategies and planning behavior
- Setting priorities among tasks and goals
- Making decisions
- Empathy
- Sensitivity to feedback (reward and punishment)
- Insight

Figure 3: Brain Development in Healthy Children and Adolescents: Longitudinal and Cross-Sectional Data (243 Scans from 145 Subjects)



The reorganization and refinement of the cortex, following a period of apparent growth and anatomical exuberance, appears to be the underlying biology of the behavioral adaptability and plasticity seen at this time of life. But the brain's circuitry, particular those parts involved in assessing risk, making long-range plans, and controlling impulses, are not yet fully developed and refined. These parts of the brain are, in a sense, still "under construction"—a process that appears to continue into the early 20's.

Scientists do not yet understand all of the forces that guide the building up or pruning down of connections between cells. Both are likely influenced by genetic and environmental factors. The roles of bacteria, viruses, nutrition, education, parenting, school, peers, drugs, video games and many other factors are hotly debated. At present, the scientific jury is still out regarding how much of this process is automatic versus how much is susceptible to manipulation and intervention. The best hypothesis at present is that learning and the formation of memories guide the building-up of connections. The best current hypothesis at present to explain the pruning phase is the "use it or lose it" principle; that is, those cells and connections that are used will survive and flourish; those that are not used will whither and die.

These concepts suggest that teens may be able to shape some aspects of their own neurological development. Unlike their time in the womb or during the first few months of life, teens can, to varying degrees, exert some control over how they spend their time and can therefore influence the sculpting of their brains for the adult years to come. Consistent with this view, neuroanatomical evidence suggests that learning and positive experience build complex, adaptive brains by increasing the potential for forming and sustaining neuronal connections—a perspective that echoes sociological and psychological tenets, as well.

Periods of exuberant growth or restructuring of the brain may also be sensitive periods when the environment can have enhanced effects. The notion of sensitive, critical periods is well understood for some fundamental processes, such as the visual system. For example, if a baby has cataracts (a clouding of the eyes' lenses), the condition must be corrected within the first two years of life if the child is to have a chance at normal vision. Similarly, songbirds must hear the singing of their species during critical periods in order to acquire their own capacity for song; and through the process of "imprinting," goslings will follow the first object they see moving after birth, even if it is a man instead of their mother. As noted above, such sensitive periods are important in humans for recovery from brain injury.

The concept of sensitive periods is more controversial and less well characterized for more advanced functions such as moral behavior, sound judgment and controlling impulsivity—functions usually attributed to the PFC. If the link between periods of dynamic brain changes and sensitivity to environmental influences does become well established scientifically, then the teen years will also be seen as a potentially critical time for developing these essential functions.

One area that changes rather dramatically during adolescence is a part of the brain having to do primarily with language abilities. Another is the connection between the cingulate, an area of the brain involved in emotions, and the hippocampus, a memory hub. The cingulate connects to the brain stem and spinal cord, modulating our physical reactions to emotions such as sweaty palms, increased heart rate, and that tense feeling in our stomach. The hippocampus helps retrieve memories, to put situations in historical context, and to remember past details about a situation that might be important. A myelin-covered bridge of axons called the superior medullary lamina connects these two areas. The laying down of myelin in this circuit is one of the most active processes in all the brain, with the myelin content doubling during the teen years (Benes, 1998). Thus, like the PFC, functions that enhance teens' ability to connect "gut feelings" with intellectual elements are under major construction.

The MRI scanner is able to look not only at the structure of the brain, but also at its function, or activity. It does this by taking advantage of the fact that oxygenated blood transmits telltale radio signals when stimulated by the scanner's strong magnetic field. By tracking these signals, functional MRI (fMRI) visualizes the brain at work, since oxygenated blood flows to the parts of the brain that are most active at any given moment, re-supplying cells with needed nutrients.

Using fMRI, investigators at Harvard University showed teens and adults pictures of faces expressing different emotions (Baird et al., 1999). When trying to identify the emotions expressed by the faces, the teens activated their amygdala, which, as noted above, is involved in the primal assessment of fear. By contrast, adults activated the frontal lobes when performing the same task and were better able to correctly identify the emotions expressed on the faces. This investigation suggests that the adults and teens processed the same information using different parts of their brains and with different results. While the adults tended to ask questions first (i.e., they more often first engaged the frontal lobes and responded with reason and logic), the teens quickly came to an intuitive conclusion (i.e., they more often first engaged amygdala and responded to the stimuli with gut emotion). Perhaps it is not so surprising that adults and teens do not always react to situations the same way or consistently see eye to eye.

It is important to stress that all of these various findings do *not* mean that the teen brain is somehow lacking; indeed, in many ways the plasticity of the teen brain is extremely well suited to meet the demands of teen life. But because the basic neuronal circuitry of decision-making is still being formed and shaped, parents and other adults who are in touch with and responsible for growing teens are still needed to help guide the process.

Section III. Behavioral evidence of a brain still developing

Controlling impulses, planning, and making decisions are crucial components of our everyday behavior. They provide the skills that we need to function in a complex world where their absence can have serious, sometimes disastrous, consequences. As noted in the previous two sections, the *neurological* structures that underlie these higher-level abilities are still maturing during adolescence. This section summarizes the *behavioral* evidence for the frontal cortex's role—and the PFC in particular—in controlling these cognitive processes; this section also assesses the extent to which teenagers possess these needed skills. Interestingly, some of the evidence available to understand the relationship of the frontal lobes to behavior comes from studies of adults with damage to this very part of the brain. In the subsections below, evidence is presented which reveals the frontal lobes' key role in the control of impulsive behavior, planning behavior, and making decisions.

Controlling impulsive behavior: adults. Adults whose frontal lobes are damaged often lack "inhibitory control;" that is, they tend to be somewhat uninhibited and impulsive. The classic example of this is the famous story of Phineas Gage, a 25-year-old Vermont railroad foreman who suffered a brain injury in l848. While packing down blasting powder, he inadvertently sparked an explosion that sent a 1.25" diameter tamping iron, more than a yard long, rocketing through the bottom of his left cheek bone and out through the top of his head. To the amazement of his co-workers, Gage only briefly lost consciousness and stood up and spoke moments later. He was quickly taken by ox cart to the nearest town, where a local physician, Dr. John Harlow, examined him. After talking with people who knew Gage before and after the accident, Harlow published an account of the incident in a medical journal 20 years later. Physically, Gage recovered well enough so that within a few months he was able to walk, speak, and demonstrate normal awareness of his surroundings. He lived for another 13 years, but his character was never the same. The formerly diligent, responsible foreman became a person who was extremely impulsive, ill mannered and unable to follow through on his obligations. "Gage was no longer Gage," said one of his friends.

People with frontal cortex damage also have problems suppressing irrelevant information in the environment, which renders them especially vulnerable to distraction. As a result, they often perform poorly on even the simplest tasks requiring sustained concentration and short-term memory. Moreover, they lack confidence when making decisions and tend to be impulsive and even aggressive (Best, Williams, & Coccaro, 2002). In brief, then, damage to the frontal cortex leads to difficulties in inhibiting and controlling inappropriate behavior, which suggest that the PFC is crucial for inhibitory and impulse control in adults.

Controlling impulsive behavior: children and adolescents. In healthy children and adolescents, impulse control and the inhibition of irrelevant responses likely develop as part of more complex functions, such as sustained and focused attention, and more complex cognitive processes, such as planning and abstract reasoning. These abilities continue to develop well into adolescence (Klenberg, Korkman, & Lahti-Nuuttila, 2001; Christ, White, Mandernach, & Keys, 2001). Examination of performance on tasks requiring subjects to now inhibit a response that was previously reinforced has found that young children (ages 7 to 12 years) display more problems inhibiting these responses than young adults (ages 21 to 24 years) (Casey et al., 1997; see also Bedard et al., 2002). Such studies show that the cognitive processes that underlie the ability to inhibit inappropriate behavior are evolving and are not fully mature in early adolescence.

Consistent with such data, fMRI studies have shown that the adolescent brain functions relatively inefficiently on selected inhibitory tasks. Although the teen brain expends a great deal of effort while performing working memory tasks involving inhibition, it fails to fully engage the neural structures, as reflected in a greater number of errors on the task (Casey et al., 1997). Such inefficient "thinking machinery" may make young adolescents more susceptible to being distracted. If neural networks responsible for the complex cognitive processing demands of inhibitory and impulse control are not yet physiologically mature, the teen brain may struggle when it is necessary to control impulsive behavior or inhibit inappropriate behavior and stay focused on a current task or situation. This may be even more of a problem if the brain is also struggling with a disorder such as Attention Deficit Hyperactivity Disorder. Of course, this is not to say that the adolescent's brain cannot control impulsive actions—only that it may be a more difficult task than for the mature brain of an adult.

Planning behavior: adults. Adult patients with damage to the frontal lobes are sometimes described as "stimulus-bound" (Luria, 1966; Lhermitte, 1986), meaning they are inflexible in adapting to changing environmental demands. This inflexibility may be due to an impaired ability to simulate internal models of the actual world (Knight & Grabowecky, 2000). Think of it this way: our judgments and planning behavior, such as assessing a particular outcome and deciding on future actions, are based on evaluations of alternatives that we generate internally: "if I do X, then Y will happen." We weigh such alternative scenarios so that we can decide on the best course of action; we also compare what *actually* happens with what *might* have happened, and then use that information to guide *future* behavior and plans. Without such mental simulations, it is difficult to avoid making the same mistakes over and over again. Thus, behavior may appear "stimulus-bound," since the individual appears to have little concern for the past or future, lacks insight and foresight, and has limited capacity to plan for the near and distant future.

Functioning well in the real world requires that we employ structured plans to guide our actions. The disorganization of behavior after frontal damage in adults is characterized by fragmented sequences of actions (Luria, 1966; Stuss & Benson, 1984). Sometimes an individual with frontal lobe damage will omit an important step in the sequence of attaining a goal, or introduce an irrelevant one. This impairment can be observed on a variety of tasks and appears to be a result of a defect in the role that purpose plays in a given action (Duncan, 1986). Patients with frontal lobe damage may also be unable to put the various parts of a plan in the right order, or they may give up altogether before goals are reached (Sirigu et al., 1995). If an individual cannot correctly order consequences and antecedents, it will be difficult to accurately gauge the reward and punishment structure of a task. As a result, the individual's behavior may seem rather odd or even bizarre.

All parts of an overall plan need to be held temporarily in mind—in a mental workspace known as "working memory"—in order to execute the behavior appropriately. Importantly, working memory requires the integrity of the frontal lobe, especially the prefrontal cortex (Diamond & Goldman-Rakic, 1986). Consistent with this view, deficits in working memory are typically observed in adult patients with frontal lobe damage (Milner, 1964). In such individuals, memory for even very simple stimuli fades very rapidly. Within a few seconds or minutes, the information needed to execute a plan may be forgotten.

In brief, then, the cognitive components associated with planning require a temporary mental workspace within which to consider possible scenarios and the range of results that certain behaviors might lead to; planning also requires the ability to sequence behavioral responses appropriately. The frontal lobes are uniquely suited to perform this task by rapidly engaging large neural networks. Damage to the frontal cortex leads to a variety of problems in adapting to the changing environment and adjusting future behavior accordingly.

Planning behavior: adolescents. It may well be that immature frontal lobes make teens vulnerable to problems in the cognitive processes that allow sound planning. For example, a study examining the cognitive components of planning in very young children, teenagers and young adults found a general age-related progression in ability. Importantly, while eight year olds' performance was superior to younger children in their ability to solve complex problems, they had certainly not reached adult performance levels on the difficult planning problems and working memory tasks (Luciana & Nelson, 1998).

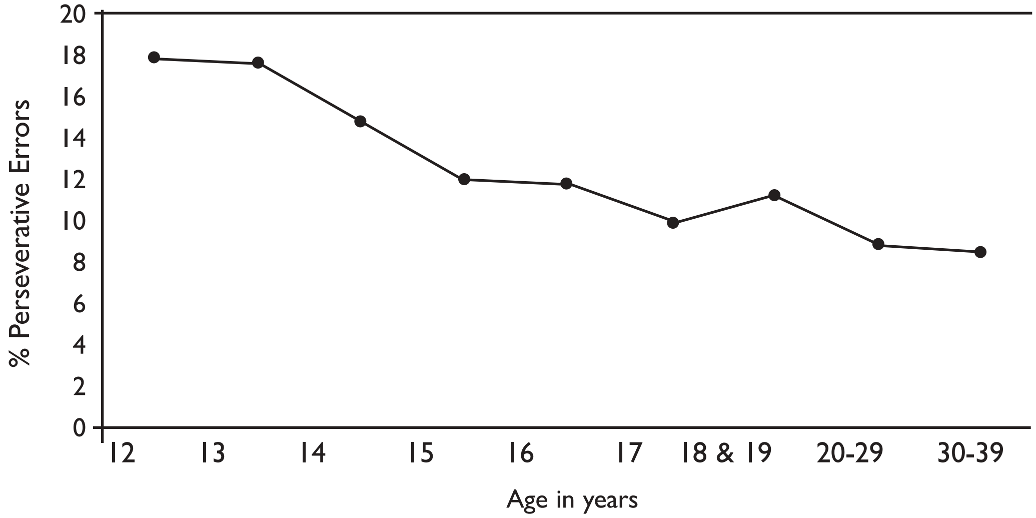
It is probably not surprising that, in general, planning abilities improve with age until adulthood. As noted above, the process of planning requires a temporary mental workspace and it is this very workspace (i.e., working memory) that is not fully formed in adolescence (Swanson, 1999). For example, in one study that examined performance on a task that specifically required advanced planning of one's movements in a sequential strategy of actions, the investigators found that 11 year olds required more extra moves (a measure of planning) to complete the task than the 15+ year olds (Anderson et al., 2001). Such data suggest that planning and the cognitive processes that underlie this ability—working memory—are not fully mature in early adolescence.

A similar task that involves future-oriented processing is the Wisconsin Card Sorting Task. This challenge requires participants to sort cards that differ by color, shape and number of geometric objects on the card face. In order to sort correctly, one must learn an abstract rule by incorporating feedback from the examiner after each attempt (i.e., whether one's decision was correct or wrong). The rule has to do with the abstract principle governing the sort, i.e. whether to sort by color, shape or number of objects on each card, irrespective of the specifc forms themselves. Once a subject has correctly sorted according to the learned rule for a certain number of trials, the rule changes arbitrarily and previously correct sorts are not incorrect. The subject must again learn the new rule by using this error feedback. That is, the subject must show flexibility in rule learning. This test is relatively sensitive and specific to prefrontal cortex function and dysfunction, and thus it is interesting to note that a certain type of error—namely, persisting on using the last rule learned even though it has changed—decreases with age. The fewer such "perseverative" errors one makes, the better one is at incorporating changing contingencies in the world (see Figure 4)

In brief, then, the prefrontal cortex is not yet mature or especially efficient during adolescence. This suggests that, as a group, teens may not always possess the cognitive workspace—the working memory—necessary for solid planning of complex behavior.

Decision-making: adults. In adults, damage to the lower middle portion of the prefrontal cortex appears to be associated with an impaired ability to simulate the future consequences of current actions, positive or negative, regardless of the emotional significance ("myopia for the future"). Thus, the person appears to be excessively influenced by immediate reward (Bechara et al., 1994, 2000). It is also possible that these individuals may simulate the outcome but not be able to attach an appropriate emotional meaning or significance to it. Research using a gambling task that models real-life decisions in the context of risk and reward has

Figure 4: Developmental decline in perseverative errors on the Wisconsin Card Sorting Test (source: Heaton et al., 1993).



found that these individuals (that is, adults with damage to the lower middle portion of the prefrontal cortex) continue to select from risky card decks even after they have accrued considerable financial debt (Bechara et al., 1996).

Given the role of the amygdala in processing the incentive value of stimuli (e.g., Bechara et al., 1999) as well as its activity during punishment (Killcross, Robbins, & Evereitt, 1997; Zalla et al., 2000), it is not surprising that damage to the amygdala has also been shown to impair performance on this gambling task. Interestingly, it is associated with blunted responses to task punishment (Bechara et al., 1999).

When we judge the odds of particular outcomes stemming from a specific behavior, simulation processes are most probably needed to imagine examples of the possibilities and generate an appropriate decision based on this imagining of the possible outcomes. It has been reliably demonstrated using what are called gambling tasks, that in healthy adults, the perception of decision problems and their evaluation of the probabilities and outcomes change as a result of how the problem is framed (Tversky & Kahneman, 1981). Specifically, people tend to take risks if it can help them avoid what they perceive of as a negative outcome (so as to avoid certain loss), and when situations are perceived as likely to be positive, people tend to prefer to avoid risk so as not to lose what they are certain to gain. Again, in adults with damage to the frontal cortex, judgments and probability estimations of this sort seem very impaired.

Furthermore, it is possible that developmental abnormalities in decision-making "circuitry" may predispose some individuals to making poor choices, as in substance abuse (Rogers et al., 1999). Indeed, a study of substance-dependent individuals found that feedback about reward, but not about punishment, guided long-term decision-making (Bechara et al., 2002). Perhaps the value placed on reward and punishment is different in individuals with certain addictions.

In summary, among adults, abnormalities in both the prefrontal cortex and the amygdala are associated with problems in decision-making (although their respective roles are different; Bechera et al., 1999). People with such challenges seem unable to use feedback to guide their responses and tend to evaluate each decision in terms of the available immediate reward.

Decision-making: adolescents. Building on such data regarding adults, it is appropriate to consider whether immature frontal lobes render adolescents vulnerable to problems in decision-making and in behavior that requires judgment under uncertainty. Adolescents do learn to reason effectively, and there is a progressive improvement in reasoning competency from childhood through adolescence and adulthood. Much of this is no doubt due to the maturing biological underpinnings of higher-level cognition. But such environmental factors as the behavior and examples set ("role modeling") by teenagers' parents and teachers and other influential people determine to a large extent the repertoire of behavioral responses that equip adolescents to deal with life situations. Teens acquire an increasing number of such strategies as they grow (Klaczynski, 2001a, 2001b). However, adolescents may also develop judgment strategies that get them into trouble because they are not appropriate to the specific circumstances. (Jacobs & Klaczynski, 2002). Despite steady improvement, older adolescents and young adults are more prone than are adults to committing what is known as the gambler's fallacy[1]. A study examining the effect on decision-making of how questions are framed found that while adolescents (mean age 14 years 10 months) responded similarly to adults, many teens

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[1] "The gambler's fallacy is a belief that the next event in a series of events will compensate for a prior sequence in which an outcome occurred with greater-than-expected frequency. For example, after a coin toss yields heads 15 times in a row, the gambler's fallacy would result in a belief that there is a greater than 50-50 chance that the next toss will yield tails, despite the fact that each coin toss is independent and the probability of either outcomes is .50" (p.148, Jacobs & Klaczynski, 2002).

were not influenced by either positive or negative framing and selected the same type of response for questions framed both ways (Chien, Lin & Worthley, 1996).

Such weaknesses in assessing probability can have serious implications. For example, one study found that young drivers seem more likely than older ones to underestimate the probability of the specific risks of certain traffic situations, and to overestimate their own ability to manage such risks (Brown & Groeger, 1988; Deery, 1999). This is consistent with the widespread notion that adolescents engage in risky behavior because of problems in judging risk appropriately and in accurately perceiving their own vulnerability. However, this assumption has been challenged by studies that found the opposite (e.g., Moore & Rosenthal, 1991, 1992), or studies that found no such differences in risk perception or sense of vulnerability (Jacobs-Quadrel, Fischhoff, & Davis, 1993). The accident-proneness in young drivers is probably in part due to their risk-taking attitudes, which lead them to prefer risk-taking options in certain traffic situations (Jessor, 1984). Clearly, the manner in which adolescents perceive the benefits of a particular risk-related behavior is also important—e.g., in experimenting with alcohol (Goldberg, Halpern-Felsher, & Millstein, 2002), and in perceptions of risk towards sexually transmitted diseases and HIV/AIDS. Interestingly (and surprisingly), a study investigating risk perception found that teenagers minimized the perceived risk for an occasional health-threatening activity, but were less optimistic about avoiding possible injury and illness than their parents were (Cohn, Macfarlane, Yanez, & Imai, 1995). Although certain decision-making skills are not fully mature in adolescence, an additional behavior such as substance abuse, may compromise this fragile capacity further.

Making sound judgments about causal relationships requires an individual to process large quantities of information about many possible combinations of antecedents and outcomes. As noted throughout this section, young adolescents have limited cognitive abilities to simultaneously process such information, hold it in-mind in working memory, and use it to guide plans and behavior. These limitations are likely traceable, in part, to brain circuitry still under construction. Naturally, the variability in the ages at which different decision-making abilities develop, as well as the abilities to avoid biased judgments, is a complex mixture of cognitive competencies and social, motivational and affective influences (Jacobs & Klaczynski, 2002). Moreover, the role of intense emotion (lodged in the amygdala) in leading to risky behavior in adolescence (through reduced risk monitoring) is difficult to ascertain, although it has been shown that situations likely to involve intense emotion have preceded car crashes in 25 percent of cases (Rothe, 1987). Clearly, this area is of great importance for future research, but unfortunately at present, "research on the development of judgment and decision making is in its infancy" (Jacobs & Klaczynski, 2002).

Less than fully mature frontal lobes likely contribute to poor decision-making, in the sense of estimations of frequencies and probabilities being less accurate than in healthy adults. The functions that underlie the complex processes involved in decision-making are maturing during the early years of life but not fully mature in early adolescence.

In sum, then, impulse control, planning for the future, appreciating cause and effect, and decision-making are important skills that rely on numerous interconnecting cognitive components that emerge as the brain develops during adolescence. Exercising these skills requires a variety of cognitive processes that are not fully mature in early adolescence. One of the important reasons that these processes are not fully mature is that the biology of the brain that underlies these processes is not fully mature. A wide variety of studies in both teens and in adults (including adults who have suffered damage to their frontal lobes) suggest that the maturation of the frontal cortex plays a pivotal role in guiding these complex behaviors, and that the fragility of these capacities in adolescence parallels the incompleteness of the biological maturation of the brain systems that make it all possible.

Future research examining the specific effects of childhood adversity on the developmental trajectory of the prefrontal cortex promises to shed further light on the extent of the fragility of cognition in adolescence. However, it is noteworthy that adversity may be of many types and thus not necessarily have similar neural correlates. Indeed, in some individuals, under some circumstances, adversity may be adaptive and of positive biological value. There will be no simple and universal solutions to increasing the probability of a successful adolescence, but it will require an appreciation of the importance of brain biology and development.

Final Thoughts

A large and compelling body of research on the neurological development of teens confirms a long-held, common sense view: teenagers are not the same as adults in a variety of key areas such as the ability to make sound judgments when confronted by complex situations, the capacity to control impulses, and the ability to plan effectively. Such limitations reflect, in part, the fact that key areas of the adolescent brain, especially the prefrontal cortex that controls many higher order skills, are not fully mature until the third decade of like. Teens are full of promise, often energetic and caring, capable of making many contributions to their communities, and able to make remarkable spurts in intellectual development and learning. But neurologically, they are not adults. They are, as we say in this paper often, a work in progress.

More research will be needed to fully understand the differences outlined in this paper, of course, but in the interim, it seems prudent for adults to think carefully about these findings. At a minimum, the data suggest that teens need to be surrounded by adults and institutions that help them learn specific skills and appropriate adult behavior. But within that fairly obvious suggestion are many more challenging and specific questions. For example, if teens are not the full neurological equivalent of adults, what specific systems and practices will best help them grow and mature in appropriate ways? What opportunities will be most effective in helping them develop the skills of judgment, planning and impulse control? What styles of parenting and teaching can most help teens develop into solid adults? Under what circumstances should teens be allowed to make their own choices and under what circumstances should directed guidance be offered and options limited? Although such questions are often discussed and debated in schools, families and communities, it is important that the answers arrived at take full note of teens' neurological development. Such biological underpinnings will not determine the answers, but they should clearly inform them.

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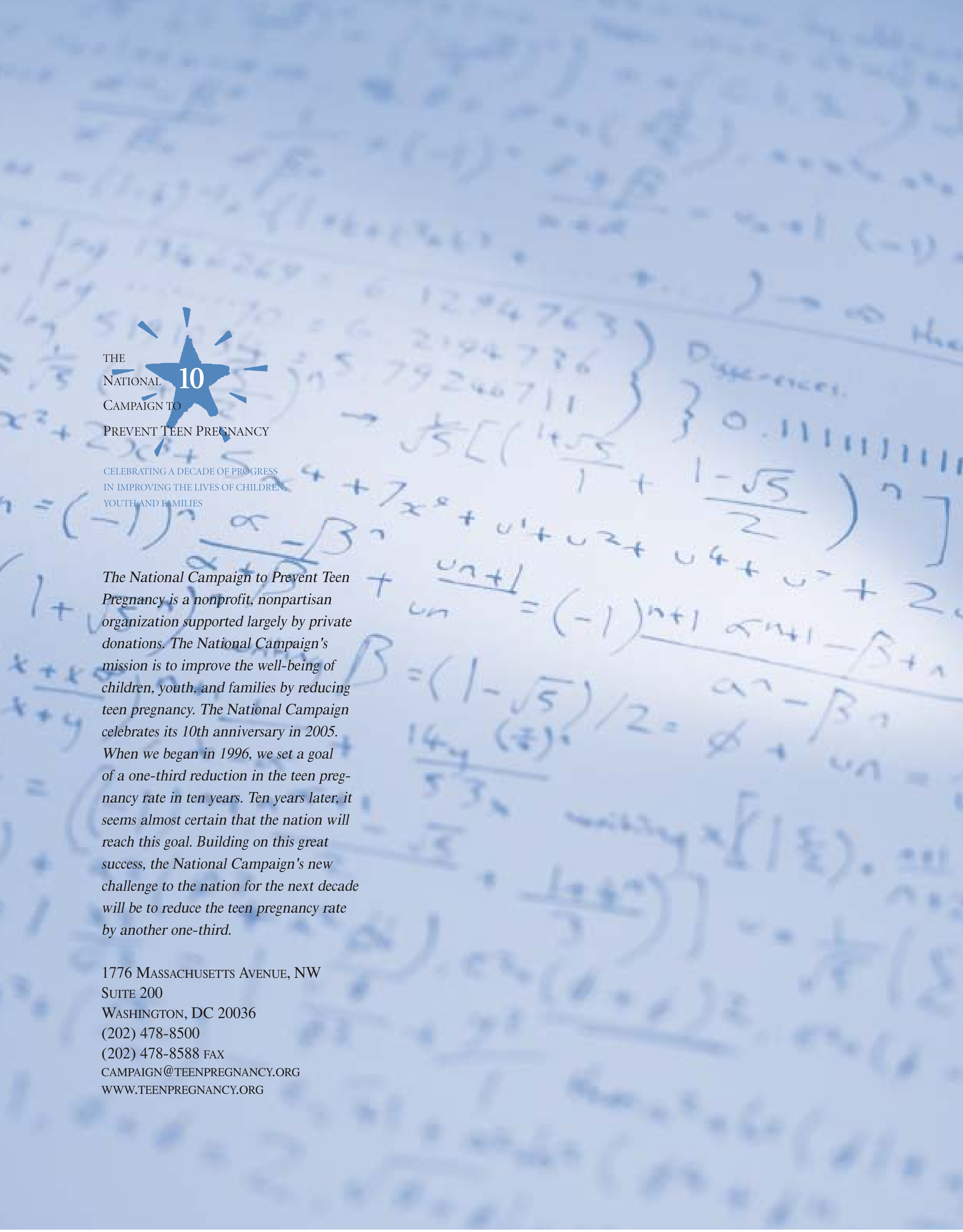

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10

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