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FAQ's on the Brain

The human brain begins forming very early in prenatal life (just three weeks after conception), but in many ways, brain development is a lifelong project. That is because the same events that shape the brain during development are also responsible for storing information—new skills and memories—throughout life. The major difference between brain development in a child versus learning an adult is a matter of degree: the brain is far more impressionable (neuroscientists use the term plastic) in early life than in maturity. This plasticity has both a positive and a negative side. On the positive side, it means that young children's brains are more open to learning and enriching influences. On the negative side, it also means that young children's brains are more vulnerable to developmental problems should their environment prove especially impoverished or un-nurturing.

Which plays a more important role in brain development, nature (genes) or nurture (environment)?

Genes and environment interact at every step of brain development, but they play very different roles. Generally speaking, genes are responsible for the basic wiring plan—for forming all of the cells (neurons) and general connections between different brain regions--while experience is responsible for fine-tuning those connections, helping each child adapt to the particular environment (geographical, cultural, family, school, peer-group) to which he belongs. An analogy that is often used is wiring a phone network: genes would specify the number of phones and the major trunk lines that connect one relay station to the next. Experience would specify the finer branches of this network-the connections between the relay station and each person's home or office.

For example, each of us is born with the potential to learn language. Our brains are programmed to recognize human speech, to discriminate subtle differences between individual speech sounds, to put words and meaning together, and to pick up the grammatical rules for ordering words in sentences. However, the particular language each child masters, the size of his vocabulary, and the exact dialect and accent with which he speaks are determined by the social environment in which he is raised--that is, the thousands of hours he has spent (beginning even before birth) listening and speaking to others. Genetic potential is necessary, but DNA alone cannot teach a child to talk.

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Does experience change the actual structure of the brain?

Yes. Brain development is "activity-dependent," meaning that the electrical activity in every circuit—sensory, motor, emotional, cognitive--shapes the way that circuit gets put together. Like computer circuits, neural circuits process information through the flow of electricity. Unlike computer circuits, however, the circuits in our brains are not fixed structures. Every experience--whether it is seeing one's first rainbow, riding a bicycle, reading a book, sharing a joke--excites certain neural circuits and leaves others inactive. Those that are consistently turned on over time will be strengthened, while those that are rarely excited may be dropped away. Or, as neuroscientists sometimes say, "Cells that fire together, wire together." The elimination of unused neural circuits, also referred to as "pruning," may sound harsh, but it is generally a good thing. It streamlines children's neural processing, making the remaining circuits work more

quickly and efficiently. Without synaptic pruning, children wouldn't be able to walk, talk, or even see properly.

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What is a "critical period" in brain development?

Pruning or selection of active neural circuits takes place throughout life, but is far more common in early childhood. Animal studies have shown that there are certain windows of time during which the young are especially sensitive to their environment: newborn mice must experience normal whisker sensation in the first few days of life or they will develop abnormal tactile sensitivity in the face region; cats must be allowed normal visual input during the first three months or their vision will be permanently impaired; and monkeys need consistent social contact during the first six months or they will end up extremely emotionally disturbed. Many of the same critical periods appear to hold for human development, although we are less certain about their exact length. Thus, babies also require normal visual input or they may suffer permanent impairment; children born with crossed or "lazy" eyes will fail to develop full acuity and depth perception if the problem is not promptly corrected. Language skills depend critically on verbal input (or sign language, for babies with hearing impairments) in the first few years or certain skills, particularly grammar and pronunciation, may be permanently impacted. The critical period for language-learning begins to close around five years of age and ends around puberty. This is why individuals who learn a new language after puberty almost always speak it with a foreign accent.

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Are there critical periods in the development of every brain function?

Probably not. In the case of visual development, certain abilities are more at-risk than others when a young child's vision is impaired by eye-crossing or other visual problems (such as congenital cataracts). Thus, two visual abilities--acuity (the perception of fine detail) and binocularity (the coordinated use of both eyes), which is especially important for depth perception--do depend on normal visual experience as a child, whereas two other visual abilities--color and peripheral vision--are not impaired by visual problems in early life. A similar distinction holds for language development: certain skills (including grammar and phonology--the ability to perceive and produce individual speech sounds) are more sensitive than others (such as vocabulary size) to a child's experience with language in the first few years of life.

We know much less about the development of other mental skills, such as emotional functioning, mathematical ability, or musical skill. If their development is comparable to vision and language, we may expect that some features will be subject to a critical period while others are not. One musical skill known as "perfect pitch"--the ability to identify a musical note without reference to a tuning note--seems to develop only in musicians who began their training before the age of seven (and then, not in all professional musicians). Similarly, a child's social-emotional development depends on a positive, nurturing attachment to a primary caregiver, based on the higher frequency of serious behavioral problems among children who were severely neglected during the first year or more of life, (such as the thousands of Romanian children reared in state-run orphanages). Comparable problems emerge among monkeys who are reared in isolation, and neuroscientists are beginning to understand how the lack of attachment in infancy alters development of emotional areas of the primate brain.

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Why does the developing brain undergo these critical periods in its development?

Neuroscientists do not yet fully understand the biological basis of these critical periods. One theory is that they correspond to a period of synaptic excess in the brain: between infancy and the early grade school years, the brain actually over-produces connections--some 50 percent more than will be preserved in adulthood. During the critical period, a child's experience--sensory, motor, emotional, and intellectual--determines which of these synapses will be preserved, through pruning of the least useful connections. In this way, each child's brain becomes better tuned to meet the challenges of his or her particular environment.

A related theory holds that learning itself creates critical periods in a child's brain. That is, the longer a child has been exposed to one type of experience or environment, the less likely he or she will be able to reverse the synaptic learning that has already taken place. Animal studies provide some support for this theory. For example, kittens that are deprived of all vision (as opposed to the vision in just one eye) in the first few months of life show a delayed critical period for visual experience, beginning from the time their deprivation ends. Similarly, songbirds normally learn their species-typical songs early in life, by listening to adults of the same species. However, when newly hatched birds of certain species are isolated, permitting them no song exposure during early life, their critical period for song learning is delayed, even as late as adulthood.

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When is the brain fully developed?

In some way, never. Our brains are continually re-shaping themselves to meet the demands of everyday life, even throughout adulthood. However, there are certain aspects of brain structure and function that do level off during development. For example, the number of neurons peaks even before birth; some 100 billion are formed during just the first five months of gestation. (Recent evidence suggests that new neurons are produced throughout life, though far less rapidly, and probably in numbers sufficient only to replace those that gradually die off.)

In spite of the great number of neurons present at birth, brain size itself increases more gradually: a newborn's brain is only about one-quarter the size of an adult's. It grows to about 80 percent of adult size by three years of age and 90 percent by age five. This growth is largely due to changes in individual neurons, which are structured much like trees. Thus, each brain

cell begins as a tiny sapling and only gradually sprouts its hundreds of long, branching dendrites. Brain growth (measured as either weight or volume) is largely due to the growth of these dendrites, which serve as the receiving point for synaptic input from other neurons.

Another way of measuring brain development is to look at the speed of neural processing. A newborn's brain works considerably more slowly than an adult's, transmitting information some sixteen times less efficiently. The speed of neural processing increases dramatically during infancy and childhood, reaching its maximum at about age fifteen. Most of this increase is due to the gradual myelination of nerve cell axons (the long "wires" that connect one neuron to another neuron's dendrites.) Myelin is a very dense, fatty substance that insulates axons much like the plastic sheath on a power cable, increasing the speed of electrical transmission and preventing cross-talk between adjacent nerve fibers. Myelination (the coating or covering of axons with myelin) begins around birth and is most rapid in the first two years but continues perhaps as late as 30 years of age.

Synaptic development is a more complicated issue. Synapses are the connecting points between the axon of one neuron and the dendrite of another. While information travels down the length of a single neuron as an electrical signal, it is transmitted across the synapse through the release of tiny packets of chemicals or, neurotransmitters. On the receiving (post-synaptic) side, special receptors for neurotransmitters change the chemical signal into an electrical signal, repeating the process in this next neuron in the chain. The number of synapses in the cerebral cortex peaks within the first few years of life, but then declines by about one third between early childhood and adolescence.

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How does nutrition affect the developing brain?

Brain development is most sensitive to a baby's nutrition between mid-gestation and two years of age. Children who are malnourished--not just fussy eaters but truly deprived of adequate calories and protein in their diet--throughout this period do not adequately grow, either physically or mentally. Their brains are smaller than normal, because of reduced dendritic growth, reduced myelination, and the production of fewer glia (supporting cells in the brain which continue to form after birth and are responsible for producing myelin). Inadequate brain growth explains why children who were malnourished as fetuses and infants suffer often lasting behavioral and cognitive deficits, including slower language and fine motor development, lower IQ, and poorer school performance.

A baby's birth weight--and brain size--do depend on the quality of his or her mother's nutrition during pregnancy. Pregnant women should gain about 20 percent of their ideal pre-pregnancy weight (e.g., 26 pounds for a 130-lb woman) to insure adequate fetal growth. This requires consuming an extra 300 calories per day, including 10-12 extra grams of protein.

After birth, brain growth depends critically on the quality of a child's nutrition. Breast milk offers the best mix of nutrients for promoting brain growth, provided that breast-fed infants receive some form of iron supplementation beginning around six months of age. (Most infant cereals are fortified with iron, and breast-fed babies require this supplementation at six months whether or not their mothers are iron-deficient.) Iron deficiency has been clearly linked to cognitive deficits in young children. Iron is critical for maintaining an adequate number of oxygen-carrying red blood cells, which in turn are necessary to fuel brain growth. Bottle-fed babies should receive formula that contains iron.

Because of the rapid pace of myelination in early life, children need a high level of fat in their diets--some 50 percent of their total calories--until about two years of age. Babies should receive most of this fat from breast milk or formula in the first year of life, and breastmilk remains an excellent source of liquid nutrition into the toddler years. However, whole cow's milk can be introduced after the first birthday, and provides an excellent source of both fat and protein for toddlers in the second year. After two years of age, children should begin transitioning to a more heart-healthy level of dietary fat (no more than 30 percent of total calories), including lower-fat cow's milk (1 or 2%).

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Prenatal Development

When does brain development begin?

Brain development begins with the formation and closure of the neural tube, the earliest nervous tissue that looks like a fat earthworm stretched out along the entire back of the embryo. The neural tube forms from the neural plate, which begins forming just sixteen days after conception. This plate lengthens and starts folding up, forming a groove at around eighteen days, which then begins fusing shut into a tube around twenty-two days post-conception. By 27 days, the tube is fully closed and has already begun its transformation into the brain and spinal cord of the embryo.

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What are neural tube defects (NTDs)?

One of the most sensitive periods in brain development occurs at the very beginning, when the neural tube is closing. If, during this fourth week after conception, the tube fails to seal in the head end of the embyro, a defect known as anencephaly results. Anencephaly means, "lack of a cerebral cortex," and is always fatal. If the tube fails to seal at its lower end, the defect is known as spina bifida. In spina bifida, part of the spinal cord may develop outside the spine, where it is highly vulnerable to damage. Spina bifida varies in severity from being totally symptomless to highly disabling, with problems including paralysis, sensory loss, and loss of bladder or bowel function.

Fortunately, NTDs can now be detected prenatally with good accuracy. Even better news comes from the recent discovery that the B vitamin, folic acid, can prevent some 60 percent of NTDs from ever developing in the first place. To be most effective, women should take a 400 microgram folic acid supplement every day, beginning about one month before conception and continuing until at least the end of the first trimester of pregnancy. (This is the amount of folic acid present in most multivitamins sold over the counter. Supplements of up to 1000 micrograms--equivalent to 1 milligram--per day are considered safe during pregnancy.) Most grains, breads and cereals sold in the U.S. are now fortified with folic acid in quantities estimated to raise the average woman's consumption by 100 micrograms per day.

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When does the fetus's brain begin to work?

Generally speaking, the central nervous system (which is composed of the brain and the spinal cord) matures in a sequence from "tail" to head. In just the fifth week after conception, the first synapses begin forming in a fetus's spinal cord. By the sixth week, these early neural connections permit the first fetal movements--spontaneous arches and curls of the whole body--that researchers can detect through ultrasound imaging. Many other movements soon follow--of the limbs (around eight weeks) and fingers (ten weeks), as well as some surprisingly coordinated actions (hiccuping, stretching, yawning, sucking, swallowing, grasping, and thumb-sucking). By the end of the first trimester, a fetus's movement repertoire is remarkably rich, even though most pregnant women can feel none of it. (Most women sense the first fetal movements around eighteen weeks of pregnancy.)

The second trimester marks the onset of other critical reflexes: continuous breathing movements (that is, rhythmic contractions of the diaphragm and chest muscles) and coordinated sucking and swallowing reflexes. These abilities are controlled by the brainstem, which sits above the spinal cord but below the higher, more recently-evolved cerebral cortex. The brainstem is responsible for many of our body's most vital functions--heart rate, breathing, and blood pressure. It is largely mature by the end of the second trimester, which is when babies first become able to survive outside the womb.

Last of all to mature is the cerebral cortex, which is responsible for most of what we think of as mental life--conscious experience, voluntary actions, thinking, remembering, and feeling. It has only begun to function around the time gestation comes to an end. Premature babies show very basic electrical activity in the primary sensory regions of the cerebral cortex--those areas that perceive touch, vision, and hearing--as well as in primary motor regions of the cerebral cortex. In the last trimester, fetuses are capable of simple forms of learning, like habituating (decreasing their startle response) to a repeated auditory stimulus, such as a loud clap just outside the mother's abdomen. Late-term fetuses also seem to learn about the sensory qualities of the womb, since several studies have shown that newborn babies respond to familiar odors (such as their own amniotic fluid) and sounds (such as a maternal heartbeat or their own mother's voice). In spite of these rather sophisticated abilities, babies enter the world with a still-primitive cerebral cortex, and it is the gradual maturation of this complex part of the brain that explains much of their emotional and cognitive maturation in the first few years of life.

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What are the most important influences on brain development before birth?

Many factors can influence fetal brain development, but most healthy pregnant women do not need to radically alter their lifestyles in order to promote optimal brain development. Good nutrition is important, since brain growth--like the growth of the rest of the fetus' body--is influenced by the quality of a pregnant woman's diet. Alcohol and cigarettes should be avoided, since these can impair the formation and wiring of brain cells. Some chemicals and forms of radiation are potentially harmful to fetal brain development, but most need concern only women exposed through their occupations--that is, those who work on farms or in factories, laboratories, hospitals, dry-cleaning stores, or other sites that expose them to dangerous chemicals, radiation, or infections.

Infections pose perhaps the greatest risk to the developing fetus' brain. Many seemingly harmless infections can seriously interrupt fetal development, including the formation and wiring of brain cells. Fortunately, most women are already immune to the most dangerous of these--rubella (which causes German measles) and varicella virus (cause of chicken pox). Other potentially harmful infections include cytomegalovirus (CMV), toxoplasmosis, and several sexually transmitted diseases (syphilis, gonorrhea, and genital herpes). Prenatal testing and treatment can minimize the risk of some of these, but generally speaking, pregnant women can best protect their babies' brains by practicing strict hygiene: wash your hands frequently, avoid sick friends and co-workers, watch out for sloppy kisses, and don't share food or drinks with anyone--even your own toddlers!

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Postnatal Development

How developed is the brain by birth?

Although it has already undergone an amazing amount of development, the brain of a newborn baby is still very much a work-in-progress. It is small--little more than one-quarter of its adult size--and strikingly uneven in its maturity. By birth, only the lower portions of the nervous system (the spinal cord and brain stem) are very well developed, whereas the higher regions (the limbic system and cerebral cortex) are still rather primitive.

The lower brain is therefore largely in control of a newborn's behavior: all of that kicking, grasping, crying, sleeping, rooting, and feeding are functions of the brain stem and spinal cord. Even the striking visual behavior of newborns--their ability to track a bold moving object, like a red ball of string, or to orient to Mom or Dad's face—is thought to be controlled by visual circuits in the brain stem. When pediatricians conduct a series of reflex tests on the newborn, they are

primarily assessing the function of these lower neural centers. These reflexes include the doll's eye maneuver (the baby's eyes stay focused forward when his head is turned to one side), the "Moro" or startle response (baby splays out arms and then slowly closes them in response to a sudden movement or feeling of falling), and even the remarkable stepping reflex (the baby "walks" when you hold him up with feet touching a flat surface).

The human brain takes time to develop, so nature has insured that the neural circuits responsible for the most vital bodily functions—breathing, heartbeat, circulation, sleeping, sucking, and swallowing—are up and running by the time a baby emerges from the protective womb. The rest of brain development can follow at a more leisurely pace, maximizing the opportunity for a baby's experience and environment to shape his emerging mind.

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What role do parents play in a baby's brain development?

Parents are another important part of the developmental equation. Infants prefer human stimuli--your face, voice, touch, and even smell--over everything else. They innately orient to people's faces and would rather listen to a speech or singing than any other kind of sound.

Just as newborn babies are born with a set of very useful instincts for surviving and orienting to their new environment, parents are equally programmed to love and respond to our babies' cues. Most adults (and children) find infants irresistible, and instinctively want to nurture and protect them. It is certainly no accident that the affection most parents feel towards their babies and the kind of attention we most want to shower them with—touching, holding, comforting, rocking, singing and talking to—provide precisely the best kind of stimulation for their growing brains. Because brain development is so heavily dependent on early experience, most babies will receive the right kind of nurturing from their earliest days, through our loving urges and parenting instincts.

In spite of all the recent hype about "making your baby smarter," scientists have not discovered any special tricks for enhancing the natural wiring phase in children's brain development. Normal, loving, responsive caregiving seems to provide babies with the ideal environment for encouraging their own exploration, which is always the best route to learning.

The one form of stimulation that has been proven to make a difference is language: infants and children who are conversed with, read to, and otherwise engaged in lots of verbal interaction show somewhat more advanced linguistic skills than children who are not as verbally engaged by their caregivers. Because language is fundamental to most of the rest of cognitive development, this simple action—talking and listening to your child—is one of the best ways to make the most of his or her critical brain-building years.

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What are the most important changes in the brain after birth?

While babies come into the world with some very useful survival reflexes, they are still strikingly helpless, in large part because the cerebral cortex is still quite immature. As the highest, most recently evolved part of the brain, the cerebral cortex is responsible for all of our conscious thoughts, feelings, memories, and voluntary actions.

Although all of the neurons in the cortex are produced before birth, they are poorly connected. In contrast to the brain stem and spinal cord, the cerebral cortex produces most of its synaptic connections after birth, in a massive burst of synapse formation known as the exuberant period. At its peak, the cerebral cortex creates an astonishing two million new synapses every second. With these new connections come a baby's many mental milestones, such as color vision, a pincer grasp, or a strong attachment to his parents.

By two years of age, a toddler's cerebral cortex contains well over a hundred trillion synapses. This period of synaptic exuberance varies in different parts of the cerebral cortex: it begins earlier in primary sensory regions, like the visual cortex or primary touch area of the cortex, while it takes off somewhat later in the temporal and frontal lobes, brain areas involved in higher cognitive and emotional functions. Nonetheless, the number of synapses remains at this peak, over-abundant level in all areas of the cerebral cortex throughout middle childhood (4-8 years of age). Beginning in the middle elementary school years and continuing until the end of adolescence, the number of synapses then gradually declines down to adult levels.

This pattern of synaptic production and pruning corresponds remarkably well to children's overall brain activity during development. Using PET imaging technology, neuroscientists have found dramatic changes in the level of energy use by children's brains over the first several years of life—from very low at birth, to a rapid rise and over-shoot between infancy and the early elementary school years, followed by a gradual decline to adult levels between middle childhood and the end of adolescence. In other words, children's brains are working very hard, especially during the period of synaptic exuberance that corresponds to the various critical periods in their mental development (see above).

Besides synapse formation and pruning, the other most significant event in postnatal brain development is myelination. Newborns' brains contain very little myelin, the dense impermeable substance that covers the length of mature brain cells and is necessary for clear, efficient electrical transmission. This lack of myelin is the main reason why babies and young children process information so much more slowly than adults—why it might take a toddler a minute or more to begin responding to a request such as "Joey, bring Mommy the teddy bear." Myelination of the cerebral cortex begins in the primary motor and sensory areas—regions that receive the first input from the eyes, ears, nose, skin, and mouth—and then progresses to "higher-order," or association regions that control the more complex integration of perception, thoughts, memories, and feelings. Myelination is a very extended process: although most areas of the brain begin adding this critical insulation within the first two years of life, some of the more complex areas in the frontal and temporal lobes continue the process throughout childhood and perhaps well into a person's 20s. Unlike synaptic pruning, myelination appears to

be largely "hard-wired." Its sequence is very predictable in all healthy children, and the only environmental factor known to influence it is severe malnutrition.

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Are there any differences in the development of boys' and girls' brains?

Yes, but they are subtle, and a product of both nature and nurture.

Neuroscientists have known for many years that the brains of men and women are not identical. Men's brains tend to be more lateralized—that is, the two hemispheres operate more independently during specific mental tasks like speaking or navigating around one's environment. For the same kinds of tasks, females tend to use both their cerebral hemispheres more equally. Another difference is size: males of all ages tend to have slightly larger brains, on average, than females, even after correcting for differences in body size.

Electrical measurements reveal differences in boys' and girls' brain function from the moment of birth. By three months of age, boys' and girls' brains respond differently to the sound of human speech. Because they appear so early in life, such differences are presumably a product of sex-related genes or hormones. We do know that testosterone levels rise in male fetuses as early as seven weeks of gestation, and that testosterone affects the growth and survival of neurons in many parts of the brain. Female sex hormones may also play a role in shaping brain development, but their function is currently not well understood.

Sex differences in the brain are reflected in the somewhat different developmental timetables of girls and boys. By most measures of sensory and cognitive development, girls are slightly more advanced: vision, hearing, memory, smell, and touch are all more acute in female than male infants. Girl babies also tend to be somewhat more socially-attuned—responding more readily to human voices or faces, or crying more vigorously in response to another infant's cry—and they generally lead boys in the emergence of fine motor and language skills.

Boys eventually catch up in many of these areas. By age three, they tend to out-perform girls in one cognitive area: visual-spatial integration, which is involved in navigation, assembling jigsaw puzzles, and certain types of hand-eye coordination. Males of all ages tend to perform better than females on tasks like mental rotation (imagining how a particular object would look if it were turned ninety degrees) while females of all ages tend to perform better than males at certain verbal tasks and at identifying emotional expression in another person's face. (It is important to emphasize that these findings describe only the average differences between boys and girls. In fact, the range of abilities within either gender is much greater than the difference between the "average girl" and the "average boy." In other words, there are plenty of boys with excellent verbal skills, and girls with excellent visual-spatial ability. While it can be helpful for parents and teachers to understand the different tendencies of the two sexes, we should not expect all children to conform to these norms.)

Genes and hormones set the ball rolling, but they do not fully account for sex differences in children's brains. Experience also plays a fundamental role. Consider, for example, the "typical" boy, with his more advanced spatial skills; he may well prefer activities like climbing or pushing trucks around—all of which further hone his visual-spatial skills. The "typical" girl, by contrast, may gravitate more toward games with dolls and siblings, which further reinforce her verbal and social skills. It is not hard to see how initial strengths are magnified—thanks to the remarkable plasticity of young children's brains—into significant differences, even before boys and girls begin preschool.

But this remarkable plasticity also provides parents and other caregivers with a wonderful opportunity to compensate for the different tendencies of boys and girls. For example, it is known that greater verbal interaction can improve young children's language skills. So the "typical boy" may especially benefit from a caregiver who engages him in lots of conversation and word play. On the other hand, the "typical girl" may benefit more from a caregiver who engages her in a jigsaw puzzle or building a block tower—activities that encourage her visual-spatial integration. The point is not to discourage children from sex-typical play (since pushing trucks or playing with dolls are great activities for any young child), but to supplement those activities with experiences that encourage the development of many competences.

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