

Do critical periods determine what we can learn and when? Neuroscientists and social scientists are probing the young brain to find the answer to this crucial question

A Critical Issue for the Brain

Walk into a toy store, and you will see a vast array of “educational” aids for newborns and infants: flash cards to promote rudimentary math, videos to teach your baby to read. A colorful soft toy just doesn’t seem to cut it anymore. Often, these products come with a not-so-subtle message: If you don’t cram as much “learning” into your child’s brain as possible before the age of three, she (or he) may never reach her full potential.

The notion that there is a “critical period” for learning in the first 3 years of life burst into the public consciousness after an April 1997 White House conference on early childhood development. The meeting drew on neurobiological evidence that a baby’s brain is still developing after birth to reinforce the need for programs to ensure normal, healthy learning experiences for underprivileged children during all the years of childhood, including the first three.

“No neuroscientist ever got up there and said ... that 0 to 3 was the most important time” for learning, says conference participant Carla Shatz, a developmental neurobiologist and chair of the neurobiology department at Harvard Medical School in Boston. But, says Shatz, a “break in logic occurred,” and in the ensuing publicity that message emerged. “As soon as this stuff hit *Newsweek* and every middle-class home in America had seen it, they totally lost sight of the fact that originally this was a motivational political message to address the needs of children

who are really at risk,” says John Bruer, president of the James S. McDonnell Foundation, which funds neuroscience research.

Although the conference’s message may have been misinterpreted—and misused—it has emphasized the need for a scientific understanding of the role played in learning and social development by so-called “critical periods.” These are defined as time windows when the brain is not only receptive to acquiring a certain kind of information, but

indeed needs that information for its continued normal development. Critical periods have been well documented for the development of sensory systems in the brain, especially vision. But many neuroscientists also believe that critical periods exist for the development of at least some of the brain functions that underlie complex learning and thinking skills. There is “overwhelming evidence for critical periods,” for example in the learning of language, says neuroscientist Janet Werker, who studies the development of language at the University of British Columbia. But others caution that the concept is being used too broadly for too many types of learning, without rigorous demonstration that such windows exist.

“There are important critical periods in human development,” says William Greenough of the University of Illinois, Urbana-Champaign. “But there is remarkably little evidence to back up the notion that there are a lot of them.” Bruer—whose book *The Myth of the First Three Years* and other writ-

the pitches of educational toy manufacturers—suggest. No critical period ends suddenly, like a window slamming shut, but rather, they “taper off gradually,” says developmental vision researcher Terri Lewis of McMaster University in Hamilton, Ontario, who has studied critical periods in human visual development.

There is also no truth to the idea that critical periods are unique to the first 3 years. For those types of learning that seem to have them, the timing varies. And in many cases, the window never seems to shut completely, and the learning, albeit more difficult, can continue into adulthood. For that reason, researchers are coming to prefer the term “sensitive periods” to critical periods. The bottom line is that although it may be easier to learn a language or take up music as a child, adults can still do it. “The truth is somewhere in between [the two extreme views], as is often the case in science,” says pediatric neurologist Peter Huttenlocher of the University of Chicago.

Early insights

There’s no doubt that critical periods do exist for certain kinds of brain development. The most famous example comes from work done by David Hubel and Torsten Wiesel at Harvard in the 1960s. They and their co-workers showed that if a kitten’s eye was closed for a time in infancy, the animal would be blind in that eye for life because the brain’s visual system had missed out on the eye’s input during a key stage of brain development. Other researchers, studying children who were born with crossed eyes or cataracts, have shown that critical periods also occur in human visual development.

Over recent decades, several types of studies have also suggested that the brain has sensitive periods for different types of learning. Some of the evidence comes from neuroscientists who have applied brain imaging and other techniques to study brain changes and correlate them with behavior and learning. Other evidence is entirely behavioral, deriving from psychiatric and education research.

Studies in this latter category have placed the most emphasis on the importance of the first 3 years. For example, psychiatric studies done in the 1950s found that children form an emotional attachment to their mother or primary caregiver during the first year or so of life. Numerous researchers have since shown that children who are securely attached, trusting their caregivers to



How much is enough? Are these children missing out if their parents don’t provide them with educational videos and toys?

ings have established him as one of the most vocal skeptics about the role of critical periods in intellectual development—worries that the hype surrounding critical periods goes far beyond what the science supports and will push society to give up on children whose early years were disadvantaged.

One thing that the scientists agree on is that critical periods, where they do exist, are not as sharply defined as the popular message following the White House conference—or

protect and nurture them, form better relationships with others later in life than do children who do not enjoy such security. What's more, their research suggested that the bonds of attachment must be in place by age 3 for such benefits to occur. Developmental psychologist Ross Thompson of the University of Nebraska, Lincoln, who studies attachment, argues that during the course of human evolution, attachment would have been so key to an infant's survival that a critical period for its formation may be built into brain development.

The attachment studies were a major rationale for the focus on age 0 to 3 as a critically important time in a child's emotional development. But Thompson notes that several studies of children who spent their early years in Romanian orphanages, deprived of the type of normal human contact that provides an opportunity to form attachments, suggest "that the window of opportunity [for attachment] is far wider than we thought. Kids rescued at 4, 5, 6 can [still] form attachments." But many of those attachments were weak or unhealthy, which may be a sign that the sensitive period tapers off at these later ages. However, without evidence of a clear end to the period, Thompson warns that it cannot be claimed as a bona fide sensitive period. An additional concern about drawing conclusions from the Romanian orphan studies, he says, is that these children were deprived in so many ways that there are many other potential reasons for their weak attachments.

Another social science study that suggests the importance of the first 3 years was conducted by education researchers Craig and Sharon Ramey of the University of Alabama, Birmingham, and Frances Campbell of the University of North Carolina, Chapel Hill. In an analysis of the impact of specially designed educational programs on more than 1000 children from underprivileged homes, they found that children enrolled from birth in preschool education programs showed greater improvement in IQ and school performance than did those enrolled in similar programs after school and during the summer in their early school years. That, says Craig Ramey, shows that opportunities missed in the first 3 to 5 years cannot necessarily be made up for later.

Studies such as these indicate that an enriched environment early in life is good for the brain. But Bruer argues that the results are being misapplied, especially by those who market "enrichment" products such as educational videos to middle-class parents. He notes that the Rameys and Campbell studied children from underprivileged environments. There is no scientific evidence, he claims, to suggest that additional enrichment beyond the normal environment for most children will of-

fer any advantage.

Not only are middle-class parents being misled about what they need to provide their children, he says, but society's attention is being diverted from the needs of the truly underprivileged, which don't end at age 3. In support of this view, he cites an animal experiment that has been widely used to promote educational aids to enrich an infant's environment. Greenough, who performed the study, agrees with Bruer that his study has been misinterpreted.

In work done over the past 2 decades, Greenough and his colleagues have shown that rats raised in so-called "complex environments"—housed with other rats, and with lots of toys to play with—develop more of the neural connections called synapses in their brains than do rats raised alone in standard lab cages. But Greenough says his studies are "more of a deprivation experiment," because the complex environments are probably closer to the normal environment for a young rat than is the bleak environment of a typical lab-rat cage. His findings, he says, suggest that extreme deprivation is detrimental, but do not address whether additional stimulation beyond that found in a normal environment is necessarily better.

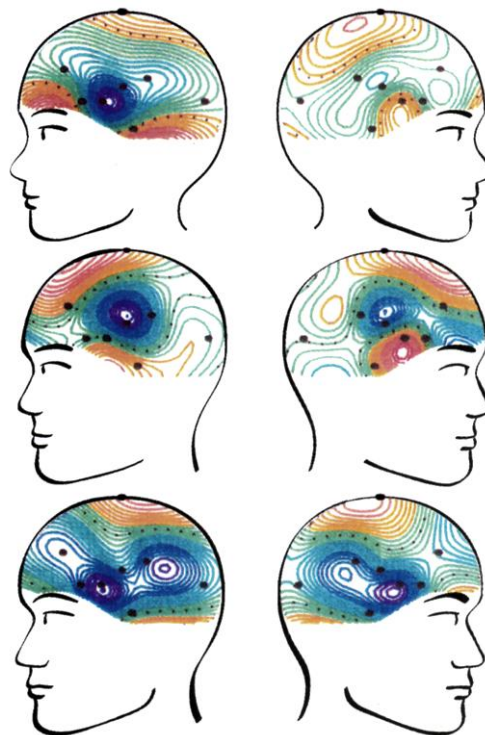
Greenough also says his study has little direct bearing on the case for enriched environments in a human infant's first 3 years, because his rats didn't enter the complex environments until they were weaned, which is equivalent to 2.5 to 5 years in human age, and they remained there until puberty. What's more, when the team exposed adult rats to similar environments, their neural connections proliferated also. "The changes occur faster in younger animals, and the magnitude is greater in younger animals, but [the effect] simply doesn't go away," Greenough says. "It is very hard to read my work ... and not to realize that it completely undermines [the] concept that everything is over by 3 years of age."

Windows for learning

Whereas the Ramey-Campbell work, as well as Greenough's, focuses on the brain's preparation for learning in general, other researchers have examined whether there are critical periods in the development of specific skills such as music and language. In a 1995 brain imaging study of musicians, for example, Thomas Elbert of the University of Konstanz in Germany and Edward Taub of

the University of Alabama, Birmingham, found that the left hand of string musicians is represented by a larger area in the brain's touch-sensing region, the somatosensory cortex, than is the left hand of nonmusicians.

The researchers' main conclusion was that the brain's ability to change in response to music training extends into adulthood. But they also found that string musicians who began their study before age 12 had the largest brain area devoted to left-hand sen-



Switching sides. Subjects who learned a language at 1 to 3 years (top) show normal predominant left-hemisphere brain activity in response to a grammatical "surprise," while those who learned the language at 4 to 6 years (middle) or 11 to 13 years (bottom) show increased right-hemisphere activity.

sation, a possible indication that the brain is more receptive to musical training earlier in life. Elbert and Taub's data might be explained by a practice effect: Those who started young had simply been playing longer. Taub acknowledges that he and Elbert didn't systematically rule out that possibility, but he says the difference in total practice time between the two groups is too small to explain the magnitude of the difference in brain organization.

Researchers looking at the receptivity of the brain to language-learning have controlled for a practice effect, and they believe they have clear evidence that the young brain can learn a language with a fluency that is only rarely achieved by older learners. In other words, there appear to be sensitive periods for language acquisition.

Some of the strongest behavioral evidence comes from cognitive scientist Elissa

Newport of the University of Rochester in New York and her colleagues. In the late 1980s, Newport, then at the University of Illinois, and graduate student Jacqueline Johnson studied 46 Chinese and Korean immigrants to the United States who became immersed in English at ages ranging from 3 to 39. To rule out a practice effect, the researchers matched their subjects for the number of years they had been using English. Then they played them recordings of spoken sentences, some of which had a grammatical error such as incorrect word order or the wrong verb tense, and asked them whether the sentence was correct.

For native speakers, the test is a breeze, says Newport, but in the immigrants the researchers found a "very systematic decline in correct responses as a function of the age at which people first arrived in the United States." People who arrived before age 5 or so did as well as native speakers, Newport says, but "each group after that is systematically lower," until the curve flattens out for those arriving after the teenage years. "It is exactly the shape you would expect from a critical period."

One could argue, Newport says, that the later learners of English did poorly not because the critical period for language learning had passed, but because the greater number of years of experience with their first language simply interfered with the learning of another language. To address that issue, Newport and her husband, Ted Supalla, turned to a special group of people who did not learn any language as infants: deaf individuals whose hearing parents don't speak American Sign Language (ASL) and who learned ASL

after entering a boarding school for the deaf at age 5 or 12. Newport and Supalla, who is himself deaf, compared a group of these delayed ASL learners to deaf ASL signers who had been immersed in ASL from birth. To rule out practice effects, they chose subjects who were 50 to 70 years old at the time of testing and had been using ASL for a minimum of 48 years.

The researchers tested production and comprehension of ASL sentences and "found the same kind of picture as in the second-language studies," says Newport. Those who began to use ASL at age 5 scored on average slightly lower than those exposed since birth, while those who didn't begin until they were 12 scored lower still.

The results of behavioral studies on lan-

guage development are buttressed by neurobiological findings. Neuroscientist Helen Neville of the University of Oregon, Eugene, has looked at brain organization in Chinese and Spanish immigrants who began to learn English at ages ranging from 2 to 16. Using brain imaging, she and her colleagues observed the subjects' brain activation patterns as they listened to sentences that had grammatical errors such as those used by Newport. "In people with delayed exposure to English, even as few as 4 years after birth, we already see a difference in the brain organization of the response to the grammatical surprise," Neville says. In

those who learned the second language before age 4, the response is entirely on the left side of the brain, where the language areas normally are, but later learners, says Neville, show more right-hemisphere activity. This suggests that the brain physically incorporates a late-learned language differently from one learned early.

Those results match what Newport and her colleagues saw when they looked at grammar ability. But grammar is only one element of language learning; other elements include phonology, the sounds of the language, and semantics, the meaning of words. And those don't necessarily have the same sensitive window. For example, Neville says, when she and her colleagues looked at the brain and behavioral responses to a so-called "semantic surprise," a sentence in which one word doesn't make sense, "late learners look the

same as early learners. It doesn't look as though there is a real tight critical or sensitive period."

Even within one aspect of language, such as phonology, there may be different windows for learning. Some parts of phonology must be learned very early to master them like a native, while others can be learned well throughout life. That means, says Neville, that "language is not a single, monolithic, homogeneous system that either does or does not display a critical period."

The basis in the brain

The brain matures throughout childhood, and Neville and others suggest that steps in the maturation process may drive the timing of sensitive periods. For example, Chicago's Huttenlocher and his colleagues have counted synapses in the postmortem brains of children of various ages. They find that synapses proliferate in most brain areas during the first year of life, after which, he says, "you have a period when the synaptic density is high, for 6 to 12 months up to 5 to 15 years, depending on the area." Then the synapse levels decline, with visual areas tending to lose their synapses first and the higher cognitive areas dropping to adult levels later. Harry Chugani at Wayne State University in Detroit and his colleagues have used positron emission tomography (PET) imaging to measure

metabolic activity in the brains of infants and children, as an indirect way of looking at synapse production and elimination, and have come to similar conclusions.

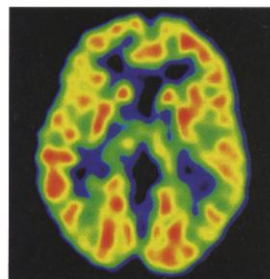
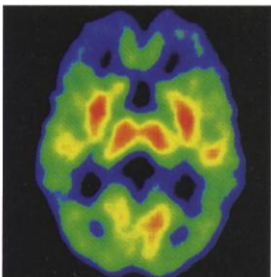
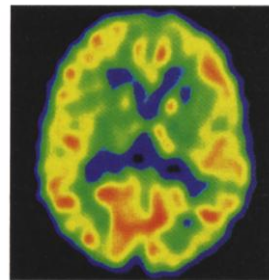
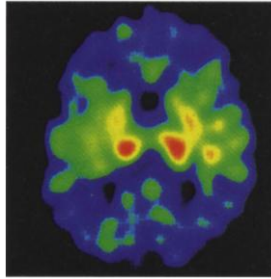
Huttenlocher notes that the basic functions of a brain area emerge during the period when he sees that initial proliferation of synapses. For example, when the synapses be-

gin to increase in the visual cortex, the child develops binocular vision. The pruning of synapses, Huttenlocher adds, appears to be associated with "the upper limit of easy learning of certain tasks," at least to a first approximation. For example, while there seem to be different sensitive periods for different aspects of language learning, 12 to 14 years is roughly the age when the general ease of language learning declines, and, says Huttenlocher, "that is about the time during which the density and number of synapses in the language areas of the brain decrease."

Despite correlations such as these, some neuroscientists and psychologists suggest that some apparent sensitive periods may be more

a function of the cumulative nature of learning than of the physical development of the brain. Developmental psychologist Alison Gopnik of the University of California, Berkeley, has found that during their fourth year of life, children learn that other individuals have thoughts and views that differ from their own. Her work suggests that this happens when it does because the children have accumulated the experiences necessary to draw conclusions about the existence of other minds.

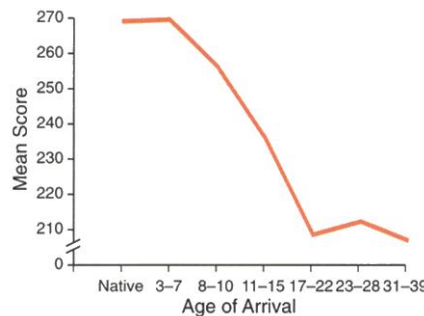
For example, she can ac-



The lights come on. These PET scans show increasing brain activity from birth to 12 months (top to bottom). This may reflect the increase in synapse number occurring during that time.

celerate the learning of these concepts by giving children special training that emphasizes the idea that others think differently. That suggests, she says, that there isn't "some maturational event in the brain" that makes the timing right, "but rather that the very things you learn enable you to learn new things."

What it may come down to, at least for some types of complex learning, is a question of whether learning drives changes in the maturing brain, or whether the maturation process controls the ease with which learning occurs. Such questions can be addressed, says Neville, as brain structures associated with different kinds of learning are identified. For example, she is currently experimenting with children to see if training that accelerates their language learning results in measurable changes in brain organization, and several research teams are beginning to use brain imaging to investigate or-



Telltale curve. The scores of immigrants on a grammar test decline with the age at which they were immersed in English and level out after puberty, a sign of a sensitive period that ends in the teen years.

ganizational changes in brain areas involved in the formation of bonds of attachment. "The work is going on; we just don't have the answers yet," says Neville. But she pre-

dicts that any answers are "not going to be either-or. We have a whole panoply of brain systems. It is likely that the answer is going to be different for each individual system."

As researchers pool their resources to nail down what role critical periods may play in learning, certain themes are emerging: Whereas younger brains may change more readily, older brains have not lost that capacity to change. And although it is clear that childhood is a privileged time for learning and one not to be wasted, there is no reason to give up hope for learning at any age. Indeed, says Rochester's Newport, the work may produce an understanding of whether the mechanisms of late-life learning differ from those of childhood. With a better understanding of such differences, says Newport, "one could think of different approaches and strategies" to improve adult education programs. And that would be good news for eager learners of all ages. —MARCIA BARINAGA

MEETING SOCIETY FOR DEVELOPMENTAL BIOLOGY

A Mile-High View of Development

BOULDER, COLORADO—Nearly 600 scientists gathered at the base of the Flatirons to discuss the growth and patterning of organisms including plants, worms, fruit flies, fish, and mice at the 59th annual meeting of the Society for Developmental Biology. Among the highlights were clues about how blind cave fish lost their eyes and how a gene that influences cell movement might help cancer spread.

A Fish's Tale

"An eye for an eye and a tooth for a tooth," declares the ancient biblical commandment. But for a population of blind cave fish, the exchange may have been an eye for a tooth—or several teeth. The theory is far from proven, but at the meeting researchers presented evidence that changes in the expression of a key gene involved in facial development might help explain the lost sight in cave fish. They suspect that during the course of evolution, the cave fish may have exchanged its sight—unnecessary in underground rivers—for more teeth and taste buds.

The Mexican tetra fish (*Astyanax mexicanus*) thrives in habitats from surface waters to lightless caves in northeastern Mexico. Although technically the same species as their light-dwelling cousins and able to interbreed with them, the *A. mexicanus* from caves are much paler and have no eyes as adults. Intrigued by different-looking fish within the same species, developmental biologist William Jeffery and postdoctoral fellow Yoshiyuki Yamamoto of the University of Maryland, College Park, have been trying

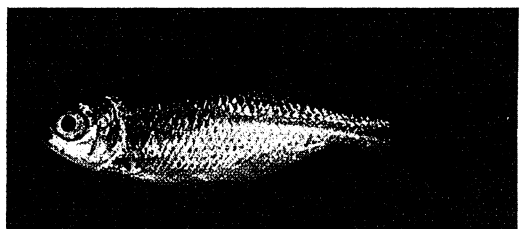
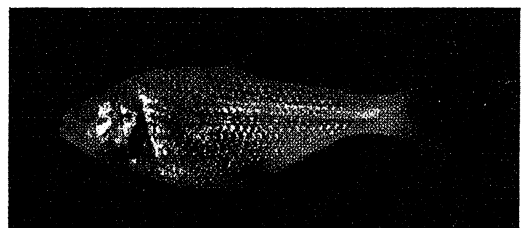
to understand how evolutionary changes in the animal's development caused the troglodytic fish to lose its eyes.

The researchers first examined the expression patterns of several eye-related genes in cave fish embryos, hoping to find clues about why the eye, which begins to develop almost normally, eventually degenerates and disappears as the fish matures. When they checked the young fish for the presence of one of the genes switched on early in eye development, called *Pax6*, they found a curious pattern: Throughout almost the entire cave fish embryo, the expression pattern of *Pax6* matched that seen in surface-dwelling *A. mexicanus*. But in the region of the embryo destined to give rise to eventual eye cells, *Pax6* was less prominent and appeared farther from the midline (a precursor of the backbone).

Previous work had shown that *Sonic hedgehog* (*Shh*), a fundamental patterning gene (named for a character from a children's computer

game) that is active at the midline, can affect expression of *Pax6*. When *Shh* is missing, for example, the mutants develop so-called cyclopia—an enlarged single eye in the middle of the forehead. To see whether *Shh* might play a role in the loss of eyes, the scientists compared the pattern of *Shh* expression in cave fish and surface fish embryos. In cave fish, they found, *Shh* appeared in a wider swath at the midline, suggesting that the cave fish might have developed a sort of anticyclopia in which extra *Shh* protein causes smaller—or missing—eyes. "We were very surprised," Jeffery says, "that our initial guess was actually correct."

To see whether they could mimic the suspected evolutionary changes in the lab, the researchers injected excess *Shh* mRNA into surface fish embryos at the two- to



Trade-off. Cave-dwelling *Astyanax mexicanus* (top) may have lost eyes but gained teeth as they diverged from their surface-dwelling cousins of the same species.