NEUROSCIENCE

HOW TO BUILD A BETTER LEARNER

Brain studies suggest new ways to improve reading, writing and arithmetic—and even social skills

By Gary Stix

Thinking cap records electrical signals from the brain of one-year-old Elise Hardwick, who is helping scientists figure out how the youngest children process sounds that make up the building blocks of language.

Photograph by Andrew Hetherington

EIGHT-MONTH-OLD LUCAS KRONMILLER has just had the surface of his largely hairless head fitted with a cap of 128 electrodes. A research assistant in front of him is frantically blowing bubbles to entertain him. But Lucas seems calm and content. He has, after all, come here, to the Infancy Studies Laboratory at Rutgers University, repeatedly since he was just four months old, so today is nothing unusual. He—like more than 1,000 other youngsters over the past 15 years—is helping April A. Benasich and her colleagues to find out whether, even at the earliest age, it is possible to ascertain if a child will go on to experience difficulties in language that will prove a burdensome handicap when first entering elementary school.

Benasich is one of a cadre of researchers employing brain-recording techniques to understand the essential processes that underlie learning. The new science of neuroeducation seeks the answers to questions that have always perplexed cognitive psychologists and pedagogues.

How, for instance, does a newborn's ability to process sounds and images relate to the child's capacity to learn letters and words a few years later? What does a youngster's capacity for staying mentally focused in preschool mean for later academic success? What can educators do to foster children's social skills—also vital in the classroom? Such studies can complement the wealth of knowledge established by psychological and educational research programs.

They also promise to offer new ideas, grounded in brain science, for making better learners and for preparing babies and toddlers for reading, writing, arithmetic, and survival in the complex social network of nursery school and beyond. Much of this work focuses on the first years of life and the early grades of elementary school because some studies show that the brain is most able to change at that time.

THE AHA! INSTANT

BENASICH STUDIES anomalies in the way the brains of the youngest children perceive sound, a cognitive process fundamental to the understanding of language, which, in turn, forms the basis for reading and writing skills. The former nurse, who went on to earn two doctorates, focuses on what she calls the aha! instant—an abrupt transition in electrical activity in the brain that signals that something new has been recognized.

Researchers at Benasich's lab in Newark, N.J., expose Lucas and other infants to tones of a certain frequency and duration. They then record a change in the electrical signals generated in the brain when a different frequency is played. Typically the electroencephalographic (EEG) trace peaks downward in response to the change—indicating that the brain essentially says, "Yes, something has changed"; a delay in the response time to the different tones means that the brain has not detected the new sound quickly enough. The research has found that this pattern of sluggish electrical activity at six months can predict language issues

IN BRIEF

The technology and research methods of the neuroscientist have started to reveal, at the most basic level, what happens in the brain when we learn something new.

As these studies mature, it may become possible for a preschooler or even an infant to engage in simple exercises to ensure that the child is cognitively equipped for school.

If successful, such interventions could potentially have a huge effect on educational practices by dramatically reducing the incidence of various learning disabilities.

Scientists, educators and parents must also beware overstated claims for brain-training methods that purport to help youngsters but have not been proved to work.

at three to five years of age. Differences in activity that persist during the toddler and preschool years can foretell problems in development of the brain circuitry that processes the rapid transitions occurring during perception of the basic units of speech. If children fail to hear or process components of speech—say, a "da" or a "pa"—quickly enough as toddlers, they may lag in "sounding out" written letters or syllables in their head, which could later impede fluency in reading. These recent findings offer more rigorous confirmation of other research by Benasich showing that children who encounter early problems in processing these sounds test poorly on psychological tests of language eight or nine years later.

If Benasich and others can diagnose future language problems in infants, they may be able to correct them by exploiting the inherent plasticity of the developing brain—its capacity to change in response to new experiences. They may even be able to improve basic functioning for an infant whose brain is developing normally. "The easiest time to make sure that the brain is getting set up in a way that's optimal for learning may be in the first part of the first year," she says.

Games, even in the crib, could be one answer. Benasich and her team have devised a game that trains a baby to react to a change in tone by turning the head or shifting the eyes (detected with a tracking sensor). When the movement occurs, a video snippet plays, a reward for good effort. In a preliminary study reported late last year, this brain training for babies, practiced over a period of weeks, enabled a group of 15 healthy infants to react more quickly to tones than a control group did. Benasich hopes that her research will confirm that the game might also assist infants impaired in processing these sounds to respond more quickly. She has started to confer with a toy developer interested in creating a mobile that could be placed on the side of a crib at home to train infants in perception of rapid sound sequences.

THE NUMBER SENSE

FLEXING COGNITIVE MUSCLES early on may also help infants tune rudimentary math skills. Stanislas Dehaene, a neuroscientist at the French National Institute of Health and Medical Research, is a leader

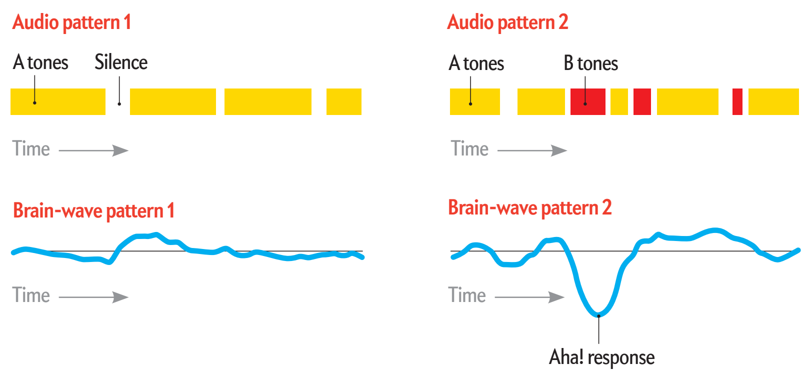
THE YOUNGEST PUPILS

Toning Up for Language: Early Education in the Crib

Scientists at Rutgers University have developed tests to determine whether babies with normal hearing process sound optimally deep within the brain (*top panel*). They are exploring whether a game they are devising (*bottom panel*) might ready the youngest children for speaking, listening, reading and writing.

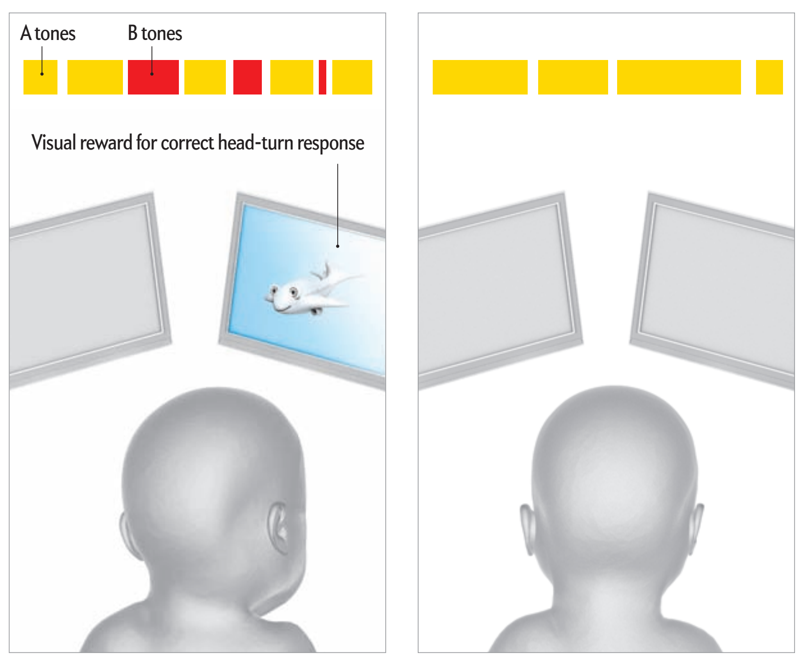
Waiting for "Aha"

The Infancy Studies Laboratory at Rutgers puts an electrode cap on babies to record brain activity while the children listen to different sounds. First, they hear high-frequency tones (*labeled A below*), which elicit a certain brain-wave pattern (*left*). Tones of different pitch (*labeled B*) intersperse with the initial tones and cause a temporary shift in the brain wave (the aha! response) as the brain detects the change (*right*). A slower or weaker response to this sudden alteration in pitch may predict language problems in later life.



A Game for Babies

Infants at Rutgers can learn to process pitch (frequency) more efficiently while also having fun. A child learns to turn the head in response to the B tones (*left*) but not to the A tones (*right*) and is rewarded with a snippet of a video for a correct response. The pace of tone sequences speeds up, and the child learns to respond more and more accurately to this fast tempo.



SOURCES: CYNTHIA ROESLER, APRIL A. BENASICH, TERESA REALPE AND NASEEM CHOUDHURY *Rutgers University*

Illustration by Bryan Christie, Graphics by Jen Christiansen in the field of numerical cognition who has tried to develop ways to help children with early math difficulties. Babies have some capability of recognizing numbers from birth. When the skill is not in place from the beginning, Dehaene says, a child may later have difficulty with arithmetic and higher math. Interventions that build this "number sense," as Dehaene calls it, may help the slow learner avoid years of difficulty in math class.

This line of research contradicts that of famed psychologist Jean Piaget, who contended that the brains of infants are blank slates, or tabula rasa, when it comes to making calculations in the crib. Children, in Piaget's view, have to develop a basic idea of what a number is from years of interacting with blocks, Cheerios or other objects. They eventually learn that when the little oat rings get pushed around a table, the location differs but the number stays the same.

The neuroscience community has amassed a body of research showing that humans and other animals have a basic numerical sense. Babies, of course, do not spring from the womb performing differential equations in their head. But experiments have found that toddlers will routinely reach for the row of M&Ms that has the most candies. And other research has demonstrated that even infants only a few months old comprehend relative size. If they see five objects being hidden behind a screen and then another five added to the first set, they convey surprise if they see only five when the screen is removed. Babies also seem to be born with other innate mathematical abilities. Besides being champion estimators, they can also distinguish exact numbers—but only up to the number three or four. Dehaene was instrumental in pinpointing a brain region—a part of the parietal lobe (the intraparietal sulcus)—where numbers and approximate quantities are represented. (Put a hand on the rear portion of the top of your head to locate the parietal lobe.)

The ability to estimate group size, which also exists in dolphins, rats, pigeons, lions and monkeys, is probably an evolutionary hand-me-down that is required to gauge whether your clan should fight or flee in the face of an enemy and to ascertain which tree bears the most fruit for picking. Dehaene, along with linguist Pierre Pica of the National Center for Scientific Research in France and colleagues, discovered more evidence for this instinctive ability through work with the Mundurukú Indians in the Brazilian Amazon, a tribe that has only an elementary lexicon for numbers. Its adult members can tell whether one array of dots is bigger than another, performing the task almost as well as a French control group did, yet most are unable to answer how many objects remain when four objects are removed from a group of six.

This approximation system is a cornerstone on which more sophisticated mathematics is constructed. Any deficit in these innate capacities can spell trouble later. In the early 1990s Dehaene hypothesized that children build on their internal ballpark estimation system for more sophisticated computations as they get older. Indeed, in the past 10 years a number of studies have found that impaired functioning of the primitive numerical estimation system in youngsters can predict that a child will perform

A NUMBER GAME

Count on It: Born to Estimate

From the time we are born, we have some concept of number. Children with deficits in this innate skill often end up struggling in later life. Stanislas Dehaene and his colleagues have created a game, the Number Race, intended to bolster our natural-born ability to estimate quantity. A preschooler judges which group of gold pieces is larger before the computer's animal avatar can steal the bigger pile (*top left*). A correct guess by the child advances his or her avatar a comparable number of spaces from its previous position; the loser moves ahead by a number equal to the smaller quantity of coins (*bottom right*). The winner is the one to reach the end of the number line first.

MODIFIED FROM "PRINCIPLES UNDERLYING THE DESIGN OF 'THE NUMBER RACE,' AN ADAPTIVE COMPUTER GAME FOR REMEDIATION OF DYSCALCULIA," BY ANNA J. WILSON, STANISLAS DEHAENE, PHILIPPE PINEL, SUSANNAH K. REVKIN, LAURENT COHEN AND DAVID COHEN, IN *BEHAVIORAL AND BRAIN FUNCTIONS*, VOL. 2; 2006

Illustration by QuickHoney

poorly in arithmetic and standard math achievement tests from the elementary years onward. "We realize now that the learning of a domain such as arithmetic has to be founded on certain core knowledge that is available already in infancy," Dehaene says.

It turns out that dyscalculia (the computational equivalent of dyslexia), which is marked by a lag in computational skills, affects 3 to 6 percent of children. Dyscalculia has received much less attention from educators than dyslexia has for reading—yet it may be just as crippling. "They earn less, spend less, are more likely to be sick, are more likely to be in trouble with the law, and need more help in school," notes a review article that appeared in *Science* in late May.

As with language, early intervention may help. Dehaene and his team devised a simple computer game they hope will enhance mathematical ability. Called the Number Race, it exercises these basic abilities in children aged four to eight. In one version, players must choose the larger of two quantities of gold pieces before a computer-controlled opponent steals the biggest pile. The game adapts automatically to the skill of the player, and at the higher levels the child must add or subtract gold before making a comparison to determine the biggest pile. If the child wins, she advances forward a number of steps equal to the gold just won. The first player to get to the last step on the virtual playing board wins.

The open-source software, which has been translated into eight languages, makes no hyperbolic claims about the benefits of brain training. Even so, more than 20,000 teachers have downloaded the software from a government-supported research institute in Finland. Today it is being tested in several controlled studies to see whether it prevents dyscalculia and whether it helps healthy children bolster their basic number sense.

GET AHOLD OF YOURSELF

THE COGNITIVE FOUNDATIONS of good learning depend heavily on what psychologists call executive function, a term encompassing such cognitive attributes as the ability to be attentive, hold what you have just seen or heard in the mental scratch pad of working memory, and delay gratification. These capabilities may predict success in school and even in the working

FACT CHECK

Five Common Myths about the Brain

Some widely held ideas about the way children learn can lead educators and parents to adopt faulty teaching principles.

MYTH: Humans use only 10 percent of their brain.

FACT The 10 percent myth (sometimes elevated to 20) is mere urban legend, one perpetrated recently by the plot of the movie *Limitless,* which pivoted around a wonder drug that endowed the protagonist with prodigious memory and analytical powers. In the classroom, teachers may entreat students to try harder, but doing so will not light up "unused" neural circuits; academic achievement does not improve by simply turning up a neural volume switch.

MYTH: "Left brain" and "right brain" people differ.

FACT The contention that we have a rational left brain and an intuitive, artistic right side is fable: humans use both hemispheres of the brain for all cognitive functions. The left brain/right brain notion originated from the realization that many (though not all) people process language more in the left hemisphere and spatial abilities and emotional expression more in the right. Psychologists have used the idea to explain distinctions between different personality types. In education, programs emerged that advocated less reliance on rational "left brain" activiities. Brain-imaging studies show no evidence of the right hemisphere as a locus of creativity. And the brain recruits both left and right sides for both reading and math.

MYTH: You must speak one language before learning another.

FACT Children who learn English at the same time as they learn French do not confuse one language with the other and so develop more slowly. This idea of interfering languages suggests that different areas of the brain compete for resources. In reality, young children who learn two languages, even at the same time, gain better generalized knowledge of language structure as a whole.

MYTH: Brains of males and females differ in ways that dictate learning abilities.

FACT Differences do exist in the brains of males and females, and the distinctive physiology may result in differences in the way their brains function. No research, though, has demonstrated gender-specific differences in how networks of neurons become connected when we learn new skills. Even if some gender differences do eventually emerge, they will likely be small and based on averages—in other words, they will not necessarily be relevant to any given individual.

MYTH: Each child has a particular learning style.

FACT The notion that a pupil tends to learn better by favoring a particular form of sensory input—a "visual learner" as opposed to one who listens better—has not received much validation in actual studies. For this and other myths, public perceptions appear to have outstripped the science. Uta Frith, a neuroscientist who chaired a British panel that looked at the promise of neuroeducation, urges parents and educators to tread cautiously: "There is huge demand by the general public to have information about neuroscience for education. As a consequence, there's an enormous supply of totally untested, untried and not very scientific methods."

SOURCES: Mind, Brain, and Education Science, by Tracey Tokuhama-Espinosa (W. W. Norton, 2010); *Understanding the Brain: The Birth of a Learning Science* (OECD, 2007); OECD Educational Ministerial Meeting, November 4–5, 2010.

world. In 1972 a famous experiment at Stanford University—"Here's a marshmallow, and I'll give you another if you don't eat this one until I return"—showed the importance of executive function. Children who could wait, no matter how much they wanted the treat, did better in school and later in life.

During the past 10 years experts have warmed to the idea of executive function as a teachable skill. An educational curriculum called Tools of the Mind has had success in some low-income school districts, where children typically do not fare as well academically compared with high-income districts. The program trains children to resist temptations and distractions and to practice tasks designed to enhance working memory and flexible thinking. In one example of a self-regulation task, a child might tell himself aloud what to do. These techniques are potentially so powerful that in centers of higher learning, economists now contemplate public policy measures to improve self-control as a way to "enhance the physical and financial health of the population and reduce the rate of crime," remark the authors of a study that appeared in the February *Proceedings of the National Academy of Sciences USA*.

Findings from neuroscience labs have recently bolstered that view and have revealed that the tedium of practice to resist metaphorical marshmallows may not be necessary. Music training can work as well. Echoing the *Battle Hymn of the Tiger Mother,* they are finding that assiduous practice of musical instruments may yield a payoff in the classroom, similar to the rationale of "tiger mom" author Amy Chua, who insisted that her daughters spend endless hours on the violin and piano. Practicing a musical instrument appears to improve attention, working memory and self-control.

Some of the research providing such findings comes from a group of neuroscientists led by Nina Kraus of Northwestern University. Kraus, head of the Auditory Neuroscience Laboratory there, grew up with a diverse soundscape at home. Her mother, a classical musician, spoke to the future neuroscientist in her native Italian, and Kraus still plays the piano, guitar and drums. "I love it—it's a big part of my life," she says, although she considers herself "just a hack musician."

Kraus has used EEG recordings to measure how the nervous system encodes pitch, timing and timbre of musical compositions—and whether neural changes that result from practicing music improve cognitive faculties. Her lab has found that music training enhances working memory and, perhaps most important, makes students better listeners, allowing them to extract speech from the all-talking-at-once atmosphere that sometimes prevails in the classroom.

Musical training as brain tonic is still in its infancy, and a number of questions remain unanswered about exactly what type of practice enhances executive function: Does it matter whether you play the piano or guitar or whether the music was written by Mozart or the Beatles? Critically, will music classes help students who have learning difficulties or who come from low-income school districts?

But Kraus points to anecdotal evidence suggesting that music training's impact extends even to academic classes. The Harmony Project provides music education to low-income youngsters in Los Angeles. In recent years, dozens of students have graduated high school and gone on to college, usually the first in their family to do so.

Program founder Margaret Martin has invited Kraus to use a mobile version of her EEG sensors and sound-processing software to measure how music affects children in the program. The hack musician is an unabashed advocate of the guitar over brain games. "If students have to choose how to spend their time between a computer game that supposedly boosts memory or a musical instrument, there's no question, in my mind, which one is more beneficial for the nervous system," Kraus says. "If you're trying to copy a guitar lead, you have to keep it in your head and try to reproduce it over and over through painstaking practice."

HYPE ALERT

AS RESEARCH CONTINUES on the brain mechanisms underlying success in the "four Rs," three traditional ones with regulation of one's impulses as the fourth, many scientists involved with neuroeducation are taking pains to avoid overhyping the interventions they are testing. They are eager to translate their findings into practical assistance for children, but they are also well aware that the research still has a long way to go. They know, too, that teachers and parents are already bombarded by a confusing raft of untested products for enhancing learning and that some highly touted tools have proved disappointing.

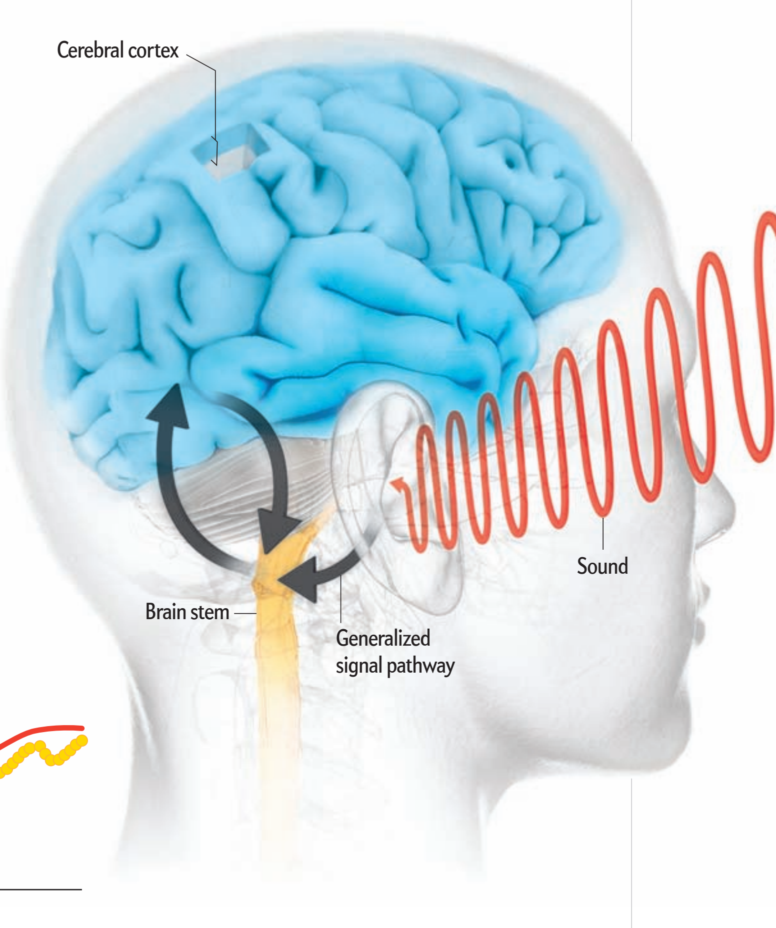
In one case in point, a small industry developed several years ago around the idea that just listening to a Mozart sonata could make a baby smarter, a contention that failed to withstand additional scrutiny. Kraus's research suggests that to gain any benefit, you have to actually play an instrument, exercising auditory-processing areas of the brain: the more you practice, the more your abilities to distinguish subtleties in sound develop. Listening alone is not sufficient.

Similarly, even some of the brain-training techniques that claim to have solid scientific proof of their effectiveness have been questioned. A meta-analysis that appeared in the March issue of the *Journal of Child Psychology and Psychiatry* reviewed studies of perhaps the best known of all brain-training methods—software called Fast ForWord, developed by Paula A. Tallal of Rutgers, Michael Merzenich of the University of California, San Francisco, and their colleagues. The analysis found no evidence of effectiveness in helping children with language or reading difficulties. As with the methods used by Benasich, a former postdoctoral fellow with Tallal, the software attempts to improve deficits in the processing of sound that can lead to learning problems. The meta-analysis provoked a sharp rebuttal from Scientific Learning, the maker of the software, which claimed that the selection criteria were too restrictive, that most studies in the analysis were poorly implemented and that the software has been improved from the time the studies were conducted.

The clichéd refrain—more research is needed—applies broadly to many endeavors in neuroeducation. Dehaene's number game still needs fine adjustments before it receives wide acceptance. One recent controlled study showed that the game helped children compare numbers, although that achievement did not carry over into better counting or arithmetic skills. A new version is being released that the researchers hope will address these problems. Yet another finding has questioned whether music training improves executive function and thereby enhances intelligence.

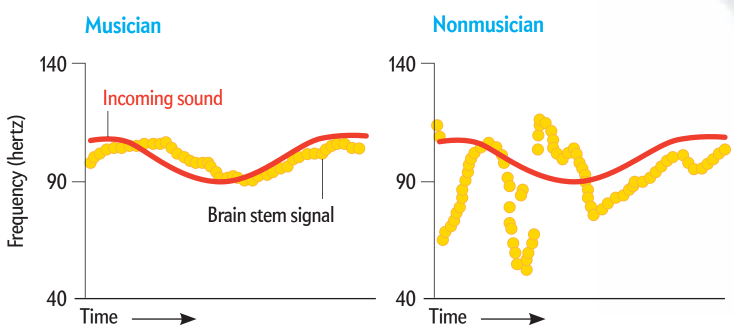
The Best Brain Training: Practice That Violin

Intensive musical training from a young age fosters skills beyond just an ability to play an instrument. The musician's concentration on the fine-grained acoustics of sound helps with language comprehension and promotes cognitive skills: attention, working memory and self-regulation.



Better Listeners

Musicians perceive sound more clearly than nonmusicians because practicing an instrument trains the entire brain. The sounds of an instrument travel from the cochlea in the inner ear to the primitive brain stem before moving to the cortex, a locus of high-level brain functions, and then back again to the brain stem and cochlea. This feedback loop allows the musician to recruit various brain areas to produce, say, the proper pitch for a tune. Monitoring of an electrical signal in the brain stem (*yellow graph line*) reveals the musician's exquisite sensitivity to pitch: the musician tracks an incoming sound wave (*red line*) more accurately than a nonmusician does.



In a nascent field, one study often contradicts another, only to be followed by a third that disputes the first two. This zigzag trajectory underlies all of science and at times leads to claims that overreach. In neuroeducation, teachers and parents have sometimes become the victims of advertising for "science-based" software and educational programs. "It's confusing. It's bewildering," says Deborah Rebhuhn, a math teacher at the Center School, a special-education institution in Highland Park, N.J., that accepts students from public schools statewide. "I don't know which thing to try. And there's not enough evidence to go to the head of the school and say that something works."

A PRESCHOOL TUNE-UP

Scientists who spend their days mulling over EEG wave forms and complex digital patterns in magnetic resonance imaging realize that they cannot yet offer definitive neuroscience-based prescriptions for improving learning. The work, however, is leading to a vision of what is possible, perhaps for Generation Z or its progeny. Consider the viewpoint of John D. E. Gabrieli, a professor of neuroscience participating in a collaborative program between Harvard University and the Massachusetts Institute of Technology. In a review article in *Science* in 2009, Gabrieli conjectured that eventually brain-based evaluation methods, combined with traditional testing, family history and perhaps genetic tests, could detect reading problems by age six and allow for intensive early intervention that might eliminate many dyslexia cases among school-age children.

One study has already found that EEGs in kindergartners predict reading ability in fifth graders better than standard psychological measures. By undergoing brain monitoring combined with standard methods, each child might be evaluated before entering school and, if warranted, be given remedial training based on the findings that are trickling in today from neuroscience laboratories. If Gabrieli's vision comes to pass, brain science may imbue the notion of individualized education with a whole new meaning—one that involves enhancing the ability to learn even before a child steps foot in the classroom. SA

Gary Stix is senior writer at Scientific American.

MORE TO EXPLORE

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Maturation of Auditory Evoked Potentials from 6 to 48: Prediction to 3 and 4 Year Language and Cognitive Abilities. Naseem Choudhoury and April A. Benasich in *Clinical Neurophysiology,* Vol. 122, pages 320–338; 2011.

The Number Sense: How the Mind Creates Mathematics. Revised edition. Stanislas Dehaene. Oxford University Press, 2011.

Nina Kraus's Auditory Neuroscience Laboratory at Northwestern University: **www.brainvolts.northwestern.edu**

SCIENTIFIC AMERICAN ONLINE
Watch a video of April A. Benasich's research at **ScientificAmerican.com/aug2011/benasich**

SOURCE: "MUSICAL EXPERIENCE SHAPES HUMAN BRAINSTEM ENCODING OF LINGUISTIC PITCH PATTERNS," BY PATRICK C. M. WONG, ERIKA SKOE, NICOLE M. RUSSO, TASHA DEES AND NINA KRAUS, IN *NATURE NEUROSCIENCE*, VOL. 10, NO. 4; APRIL 2007 *(graphs)*

Illustration by Bryan Christie, Graphics by Jen Christiansen