

A baby's brain is a work in progress, trillions of neurons waiting to be wired into a mind. The experiences of childhood, pioneering research shows, help form the brain's circuits—for music and math, language and emotion.

Your Child's Brain

Sharon Begley

YOU HOLD YOUR NEWBORN SO his sky-blue eyes are just inches from the brightly patterned wallpaper. *ZZZt*: a neuron from his retina makes an electrical connection with one in his brain's visual cortex. You gently touch his palm with a clothespin; he grasps it, drops it, and you return it to him with soft words and a smile. *Crackle*: neurons from his hand strengthen their connection to those in his sensory-motor cortex. He cries in the night; you feed him, holding his gaze because nature has seen to it that the distance from a parent's crooked elbow to his eyes exactly matches the distance at which a baby focuses. *Zap*: neurons in the brain's amygdala send pulses of electricity through the circuits that control emotion. You hold him on your lap and talk . . . and neurons from his ears start hard-wiring connections to the auditory cortex.

And you thought you were just playing with your kid.

When a baby comes into the world her brain is a jumble of neurons, all waiting to be woven into the intricate tapestry of the mind. Some of the neurons have already been hard-wired, by the genes in the fertilized egg, into circuits that command breathing or control heartbeat, regulate body temperature or produce reflexes. But trillions upon trillions

more are like the Pentium chips in a computer before the factory preloads the software. They are pure and of almost infinite potential, unprogrammed circuits that might one day compose rap songs and do calculus, erupt in fury and melt in ecstasy. If the neurons are used, they become integrated into the circuitry of the brain by connecting to other neurons; if they are not used, they may die. It is the experiences of childhood, determining which neurons are used, that wire the circuits of the brain as surely as a programmer at a keyboard reconfigures the circuits in a computer. Which keys are typed—which experiences a child has—determines whether the child grows up to be intelligent or dull, fearful or self-assured, articulate or tongue-tied. Early experiences are so powerful, says pediatric neurobiologist Harry Chungani of Wayne State University, that "they can completely change the way a person turns out."

By adulthood the brain is crisscrossed with more than 100 billion neurons, each reaching out to thousands of others so that, all told, the brain has more than 100 trillion connections. It is those connections—more than the number of galaxies in the known universe—that give the brain its unrivaled powers. The traditional view was that the wiring diagram is predetermined, like one for a new house,

by the genes in the fertilized egg. Unfortunately, even though half the genes—50,000—are involved in the central nervous system in some way, there are not enough of them to specify the brain's incomparably complex wiring. That leaves another possibility: genes might determine only the brain's main circuits, with something else shaping the trillions of finer connections. That something else is the environment, the myriad messages that the brain receives from the outside world. According to the emerging paradigm, "there are two broad stages of brain wiring," says developmental neurobiologist Carla Shatz of the University of California, Berkeley: "an early period, when experience is not required, and a later one, when it is."

Yet, once wired, there are limits to the brain's ability to create itself. Time limits. Called "critical periods," they are windows of opportunity that nature flings open, starting before birth, and then slams shut, one by one, with every additional candle on the child's birthday cake. In the experiments that gave birth to this paradigm in the 1970s, Torsten Wiesel and David Hubel found that sewing shut one eye of a newborn kitten rewired its brain: so few neurons connected from the shut eye to the visual cortex that the animal was blind even after its eye was reopened.

The Logical Brain



SKILL: Math and logic

LEARNING WINDOW: Birth to 4 years

WHAT WE KNOW: Circuits for math reside in the brain's cortex, near those for music. Toddlers taught simple concepts, like one and many, do better in math. Music lessons may help develop spatial skills.

WHAT WE CAN DO ABOUT IT: Play counting games with a toddler. Have him set the table to learn one-to-one relationships—one plate, one fork per person. And, to hedge your bets, turn on a Mozart CD.

Such rewiring did not occur in adult cats whose eyes were shut. Conclusion: there is a short, early period when circuits connect the retina to the visual cortex. When brain regions mature dictates how long they stay malleable. Sensory areas mature in early childhood; the emotional limbic system is wired by puberty; the frontal lobes—seat of understanding—develop at least through the age of 16.

The implications of this new understanding are at once promising and disturbing. They suggest that, with the right input at the right time, almost anything is possible. But they imply, too, that if you miss the window you're playing with a handicap. They offer an explanation of why the gains a toddler makes in Head Start are so often evanescent: this intensive instruction begins too late to fundamentally rewire the brain. And they make clear the mistake of postponing instruction in a second language (see box, "Why Do Schools Flunk Biology?"). As Chugani asks, "What idiot decreed that foreign-language instruction not begin until high school?"

Neurobiologists are still at the dawn of understanding exactly which kinds of experiences, or sensory input, wire the brain in which ways. They know a great deal about the circuit for vision. It has a neuron-growth spurt at the age of 2 to 4 months, which corresponds to when babies start to really notice the world, and peaks at 8 months, when each neuron is connected to an astonishing 15,000 other neurons. A baby whose eyes are clouded by cataracts from birth will, despite cataract-removal surgery at the age of 2, be forever blind. For other systems, researchers know what happens, but not—at the level of neurons and molecules—how. They nevertheless remain confident that cognitive abilities work much like sensory ones, for the brain is parsimonious in how it conducts its affairs: a mechanism that works fine for wiring vision is not likely to be abandoned when it comes to circuits for music. "Connections are not forming willy-nilly," says Dale Purves of Duke University, "but are promoted by activity."

Language: Before there are words, in the world of a newborn, there are sounds. In English they are phonemes such as sharp ba's and da's, drawn-out ee's and ll's and sibilant sss's. In Japanese they are different—barked hi's, merged rr/ll's. When a child hears a phoneme over and over, neurons from his ear stimulate the formation of dedicated connections in his brain's auditory cortex. This "perceptual map," explains Patricia Kuhl of the University of Washington, reflects the apparent distance—and thus the similarity—between sounds. So in English-speakers, neurons in the auditory cortex that respond to "ra" lie far from those that respond to "la." But for Japanese, where the sounds are nearly identical, neurons that respond to "ra" are practically intertwined, like L.A. freeway spaghetti, with those for "la." As a result, a Japanese-speaker will have trouble distinguishing the two sounds.

Researchers find evidence of these tendencies across many languages. By 6 months of age, Kuhl reports, infants in English-speaking homes already have different auditory maps (as shown by electrical measurements that identify which neurons respond to different

sounds) from those in Swedish-speaking homes. Children are functionally deaf to sounds absent from their native tongue. The map is completed by the first birthday. "By 12 months," says Kuhl, "infants have lost the ability to discriminate sounds that are not significant in their language. And their babbling has acquired the sound of their language."

Kuhl's findings help explain why learning a second language after, rather than with, the first is so difficult. "The perceptual map of the first language constrains the learning of a second," she says. In other words, the circuits are already wired for Spanish, and the remaining undedicated neurons have lost their ability to form basic new connections for, say, Greek. A child taught a second language after the age of 10 or so is unlikely ever to speak it like a native. Kuhl's work also suggests why related languages such as Spanish and French are easier to learn than unrelated ones: more of the existing circuits can do double duty.

With this basic circuitry established, a baby is primed to turn sounds into words. The more words a child hears, the faster she learns language, according to psychiatrist Janellen Huttenlocher of the University of Chicago. Infants whose mothers spoke to them a lot knew 131 more words at 20 months than did babies of more taciturn, or less involved, mothers; at 24 months, the gap had widened to 295 words. (Presumably the findings would also apply to a father if he were the primary caregiver.) It didn't matter which words the mother used—monosyllables seemed to work. The sound of words, it seems, builds up neural circuitry that can then absorb more words, much as creating a computer file allows the user to fill it with prose. "There is a huge vocabulary to be acquired," says Huttenlocher, "and it can only be acquired through repeated exposure to words."

Music: Last October researchers at the University of Konstanz in Germany reported that exposure to music rewires neural

The Language Brain



SKILL: Language

LEARNING WINDOW: Birth to 10 years

WHAT WE KNOW: Circuits in the auditory cortex, representing the sounds that form words, are wired by the age of 1. The more words a child hears by 2, the larger her vocabulary will grow. Hearing problems can impair the ability to match sounds to letters.

WHAT WE CAN DO ABOUT IT: Talk to your child—a lot. If you want her to master a second language, introduce it by the age of 10. Protect hearing by treating ear infections promptly.

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circuits. In the brains of nine string players examined with magnetic resonance imaging, the amount of somatosensory cortex dedicated to the thumb and fifth finger of the left hand—the fingering digits—was significantly larger than in nonplayers. How long the players practiced each day did not affect the cortical map. But the age at which they had been introduced to their muse did: the younger the child when she took up an instrument, the more cortex she devoted to playing it.

Like other circuits formed early in life, the ones for music endure. Wayne State's Chugani played the guitar as a child, then gave it up. A few years ago he started taking piano lessons with his young daughter. She learned easily, but he couldn't get his fingers to follow his wishes. Yet when Chugani recently picked up a guitar, he found to his delight that "the songs are still there," much like the muscle memory for riding a bicycle.

Math and logic: At UC Irvine, Gordon Shaw suspected that all higher-order thinking is characterized by similar patterns of neuron firing. "If you're working with little kids," says Shaw, "you're not going to teach them higher mathematics or chess. But they are interested in and can process music." So Shaw and Frances Rauscher gave 19 preschoolers piano or singing lessons. After eight months, the researchers found, the children "dramatically improved in spatial reasoning," compared with children given no music lessons, as shown in their ability to work mazes, draw geometric figures and copy patterns of two-color blocks. The mechanism behind the "Mozart effect" remains murky, but Shaw suspects that when children exercise cortical neurons by listening to classical music, they are also strengthening circuits used for mathematics. Music, says the UC team, "excites the inherent brain patterns and enhances their use in complex reasoning tasks."

Emotions: The trunk lines for the circuits controlling emotion are laid down before birth. Then parents take over. Perhaps the strongest influence is what psychiatrist Daniel Stern calls attunement—whether caregivers "play back a child's inner feelings." If a baby's squeal of delight at a puppy is met with a smile and hug, if her excitement at seeing a plane overhead is mirrored, circuits for these emotions are reinforced. Apparently, the brain uses the same pathways to generate an emotion as to respond to one. So if an emotion is reciprocated, the electrical and chemical signals that produced it are reinforced. But if emotions are repeatedly met with indifference or a clashing response—Baby is proud of building a skyscraper out of Mom's best pots, and Mom is terminally annoyed—those circuits become confused and fail to strengthen. The key here is "repeatedly": one dismissive harrumph will not scar a child for life. It's the pattern that counts, and it can be very powerful: in one of Stern's studies, a baby whose mother never matched her level of excitement became extremely passive, unable to feel excitement or joy.

Experience can also wire the brain's "calm down" circuit, as Daniel Goleman describes in his best-selling "Emotional Intelligence." One father gently soothes his crying infant, another drops him into his crib; one mother hugs the toddler who just skinned her knee, another screams "It's your own stupid fault!" The first responses are attuned to the child's distress; the others are wildly out of emotional sync. Between 10 and 18 months, a cluster of cells in the rational prefrontal cortex is busy hooking up to the emotion regions. The circuit seems to grow into a control switch, able to calm agitation by infusing reason into emotion. Perhaps parental soothing trains this circuit, strengthening the neural connections that form it, so that the child learns how to calm herself down. This all happens

so early that the effects of nurture can be misperceived as innate nature.

Stress and constant threats also rewire emotion circuits. These circuits are centered on the amygdala, a little almond-shaped structure deep in the brain whose job is to scan incoming sights and sounds for emotional content. According to a wiring diagram worked out by Joseph LeDoux of New York University, impulses from eye and ear reach the amygdala before they get to the rational, thoughtful neocortex. If a sight, sound or experience has proved painful before—Dad's drunken arrival home was followed by a beating—then the amygdala floods the circuits with neurochemicals before the higher brain knows what's happening. The more often this pathway is used, the easier it is to trigger: the mere memory of Dad may induce fear. Since the circuits can stay excited for days, the brain remains on high alert. In this state, says neuroscientist Bruce Perry of Baylor College of Medicine, more circuits attend to nonverbal cues—facial expressions, angry noises—that warn of impending danger. As a result, the cortex falls behind in development and has trouble assimilating complex information such as language.

Movement: Fetal movements begin at 7 weeks and peak between the 15th and 17th weeks. That is when regions of the brain controlling movement start to wire up. The critical period lasts a while: it takes up to two years for cells in the cerebellum, which controls posture and movement, to form functional circuits. "A lot of organization takes place using information gleaned from when the child moves about in the world," says William Greenough of the University of Illinois. "If you restrict activity you inhibit the formation of synaptic connections in the cerebellum." The child's initially spastic movements send a signal to the brain's motor cortex; the more the arm, for instance, moves, the stronger the circuit, and the better the brain will become at moving the arm intentionally and fluidly. The window lasts only a few years: a child immobilized in a body cast until the age of 4 will learn to walk eventually, but never smoothly.

The Musical Brain



SKILL: Music

LEARNING WINDOW: 3 to 10 years

WHAT WE KNOW: String players have a larger area of their sensory cortex dedicated to the fingering digits on their left hand. Few concert-level performers begin playing later than the age of 10. It is much harder to learn an instrument as an adult.

WHAT WE CAN DO ABOUT IT: Sing songs with children. Play structured, melodic music. If a child shows any musical aptitude or interest, get an instrument into her hand early.

THERE ARE MANY MORE CIRCUITS to discover, and many more environmental influences to pin down. Still, neuro labs are filled with an unmistakable air of optimism these days. It stems from a growing understanding of how, at the level of nerve cells and molecules, the brain's circuits form. In the beginning, the brain-to-be consists of only a few advance scouts breaking trail: within a week of conception they march out of the embryo's "neural tube," a cylinder of cells extending from head to tail. Multi-

plying as they go (the brain adds an astonishing 250,000 neurons per minute during gestation), the neurons clump into the brain stem which commands heartbeat and breathing, build the little cerebellum at the back of the head which controls posture and movement, and form the grooved and rumpled cortex wherein thought and perception originate. The neural cells are so small, and the distance so great, that a neuron striking out for what will be the prefrontal cortex migrates a distance equivalent to a human's walking from New York to California, says developmental neurobiologist Mary Beth Hatten of Rockefeller University.

Only when they reach their destinations do these cells become true neurons. They grow a fiber called an axon that carries electrical signals. The axon might reach only to a neuron next door, or it might wend its way clear across to the other side of the brain. It is the axonal connections that form the brain's circuits. Genes determine the main highways along which axons travel to make their connection. But to reach particular target cells, axons follow chemical cues strewn along their path. Some of these chemicals attract: this way to the motor cortex! Some repel: no, that way to the olfactory cortex. By the fifth month of gestation most axons have reached their general destination. But like the prettiest girl in the bar, target cells attract way more suitors—axons—than they can accommodate.

How does the wiring get sorted out? The baby neurons fire electrical pulses once a minute, in a fit of what Berkeley's Shatz calls auto-dialing. If cells fire together, the target cells "ring" together. The target cells then release a flood of chemicals, called trophic factors, that strengthen the incipient connections. Active neurons respond better to trophic factors than inactive ones, Barbara Barres of Stanford University reported in October. So neurons that are quiet when others throb lose their grip on the target cell. "Cells that fire together wire together," says Shatz.

The same basic process continues after birth. Now, it is not an auto-dialer that sends signals, but stimuli from the senses. In experiments with rats, Illinois's Greenough found that animals raised with playmates and toys and other stimuli grow 25 percent more synapses than rats deprived of such stimuli.

Rats are not children, but all evidence suggests that the same rules of brain development hold. For decades Head Start has fallen short of the high hopes invested in it: the children's IQ gains fade after about three years. Craig Ramey of the University of Alabama suspected the culprit was timing: Head Start enrolls 2-, 3- and 4- year-olds. So in 1972 he launched the Abecedarian Project. Children from 20 poor families were assigned to one of four groups: intensive early education in a day-care center from about 4 months to age 8, from 4 months to 5 years, from 5 to 8

SCHOOLS

Why Do Schools Flunk Biology?

BY LYNNELL HANCOCK

BIOLOGY IS A STAPLE AT MOST American high schools. Yet when it comes to the biology of the students themselves—how their brains develop and retain knowledge—school officials would rather not pay attention to the lessons. Can first graders handle French? What time should school

start? Should music be cut? Biologists have some important evidence to offer. But not only are they ignored, their findings are often turned upside down.

Force of habit rules the hallways and classrooms. Neither brain science nor education research has been able to free the majority of America's schools from their 19th-century roots. If more administrators were tuned into brain research, scientists argue, not only would schedules change, but subjects such as foreign language and geometry would be offered to much younger children. Music and gym would be daily re-

quirements. Lectures, work sheets and rote memorization would be replaced by hands-on materials, drama and project work. And teachers would pay greater attention to children's emotional connections to subjects. "We do more education research than anyone else in the world," says Frank Vellutino, a professor of educational psychology at State University of New York at Albany, "and we ignore more as well."

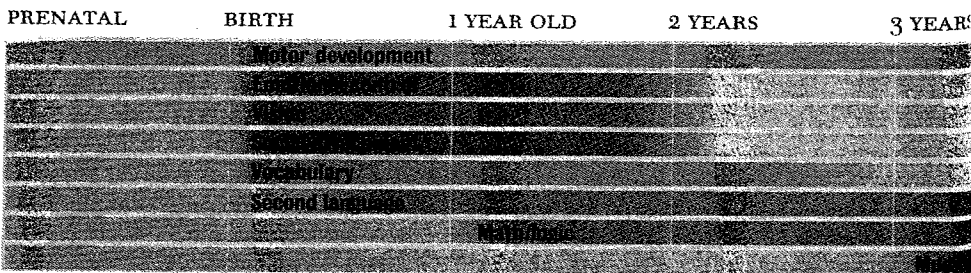
Plato once said that music "is a more potent instrument than any other for education." Now scientists know why. Music, they believe, trains the brain for

higher forms of thinking. Researchers at the University of California, Irvine, studied the power of music by observing two groups of preschoolers. One group took piano lessons and sang daily in chorus. The other did not. After eight months the musical 3-year-olds were expert puzzlemasters, scoring 80 percent higher than their playmates did in spatial intelligence—the ability to visualize the world accurately.

This skill later translates into complex math and engineering skills. "Early music training can enhance a child's ability to reason," says Irvine physicist Gordon Shaw. Yet music education is often the first "frill" to be cut when school budgets shrink. Schools on average have only one music teacher for every 500 children, according to the National Commission on Music Education.

Then there's gym—an other expendable hour by most school standards. Only 36 percent of schoolchildren today are required to partic-

The Windows of Opportunity



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ipate in daily physical education. Yet researchers now know that exercise is good not only for the heart. It also juices up the brain, feeding it nutrients in the form of glucose and increasing nerve connections—all of which make it easier for kids of all ages to learn. Neuroscientist William Greenough confirmed this by watching rats at his University of Illinois at Urbana-Champaign lab. One group did nothing. A second exercised on an automatic treadmill. A third was set loose in a Barnum & Bailey obstacle course requiring the rats to perform acrobatic feats. These "supersmart" rats grew "an enormous amount of gray matter" compared with their sedentary partners, says Greenough.

Of course, children don't ordinarily run such gantlets; still, Greenough believes, the results are significant. Numerous studies, he says, show that children who exercise regularly do better in school.

The implication for schools goes beyond simple exercise. Children also need to be more physically active in the classroom, not sitting quietly in their seats memorizing subtraction tables. Knowledge is retained

longer if children connect not only aurally but emotionally and physically to the material, says University of Oregon education professor Robert Sylwester in "A Celebration of Neurons."

Good teachers know that lecturing on the American Revolution is far less effective than acting out a battle. Angles and dimensions are better understood if children chuck their work sheets and build a complex model to scale. The smell of the glue enters memory through one sensory system, the touch of the wood blocks another, the sight of the finished model still another. The brain then creates a multidimensional mental model of the experience—one easier to retrieve. "Explaining a smell," says Sylwester, "is not as good as actually smelling it."

Scientists argue that children are capable of far more at younger ages than schools generally realize. People obviously continue learning their whole lives, but the optimum "windows of opportunity for learning" last until about the age of 10 or 12, says Harry Chugani of Wayne State University's Children's Hospital of Michigan. Chugani determined this

by measuring the brain's consumption of its chief energy source, glucose. (The more glucose it uses, the more active the brain.) Children's brains, he observes, gobble up glucose at twice the adult rate from the age of 4 to puberty. So young brains are as primed as they'll ever be to process new information. Complex subjects such as trigonometry or foreign language shouldn't wait for puberty to be introduced. In fact, Chugani says, it's far easier for an elementary-school child to hear and process a second language—and even speak it without an accent. Yet most U.S. districts wait until junior high to introduce Spanish or French—after the "windows" are closed.

Reform could begin at the beginning. Many sleep researchers now believe that most teens' biological clocks are set later than those of their fellow humans. But high school starts at 7:30 a.m., usually to accommodate bus schedules. The result can be wasted class time for whole groups of kids. Making matters worse, many kids have trouble readjusting their natural sleep rhythm. Dr. Richard Allen of Johns Hopkins University found that teens went to sleep at

the same time whether they had to be at school by 7:30 a.m. or 9:30 a.m. The later-to-rise teens not only get more sleep, he says; they also get better grades. The obvious solution would be to start school later when kids hit puberty. But at school, there's what's obvious, and then there's tradition.

Why is this body of research rarely used in most American classrooms? Not many administrators or school-board members know it exists, says Linda Darling-Hammond, professor of education at Columbia University's Teachers College. In most states, neither teachers nor administrators are required to know much about how children learn in order to be certified. What's worse, she says, decisions to cut music or gym are often made by noneducators, whose concerns are more often monetary than educational. "Our school system was invented in the late 1800s, and little has changed," she says. "Can you imagine if the medical profession ran this way?"

With PAT WINGERT and MARY HAGER in Washington

Circuits in different regions of the brain mature at different times. As a result, different circuits are most sensitive to life's experiences at different ages. Give your children the stimulation they

need when they need it, and anything's possible. Stumble, and all bets are off.

4 YEARS

5 YEARS

6 YEARS

7 YEARS

8 YEARS

9 YEARS

7. DEVELOPMENT

years, or none at all. What does it mean to "educate" a 4-month-old? Nothing fancy: blocks, beads, talking to him, playing games such as peek-a-boo. As outlined in the book "Learning games,"* each of the 200-odd activities was designed to enhance cognitive, language, social or motor development. In a recent paper, Ramey and Frances Campbell of the University of North Carolina report that children enrolled in Abecedarian as preschoolers still scored higher in math and reading at the age of 15 than untreated children. The children still retained an average IQ edge of 4.6 points. The earlier the children were enrolled, the more enduring the gain. And intervention after age 5 conferred no IQ or academic benefit.

All of which raises a troubling question. If the windows of the mind close, for the most part, before we're out of elementary school, is all hope lost for children whose parents did not have them count beads to stimulate their math circuits, or babble to them to build their language loops? At one level, no: the brain retains the ability to learn throughout life, as witness anyone who was befuddled by Greek in college only to master it during retirement. But on a deeper level the news is sobering. Chil-

dren whose neural circuits are not stimulated before kindergarten are never going to be what they could have been. "You want to say that it is never too late," says Joseph Sparling, who designed the Abecedarian curriculum. "But there seems to be something very special about the early years."

And yet . . . there is new evidence that certain kinds of intervention can reach even the older brain and, like a microscopic screwdriver, rewire broken circuits. In January, scientists led by Paula Tallal of Rutgers University and Michael Merzenich of UC San Francisco described a study of children who have "language-based learning disabilities"—reading problems. LLD affects 7 million children in the United States. Tallal has long argued that LLD arises from a child's inability to distinguish short, staccato sounds—such as "d" and "b." Normally, it takes neurons in the auditory cortex something like .015 second to respond to a signal from the ear, calm down and get ready to respond to the next sound; in LLD children, it takes five to 10 times as long. (Merzenich speculates that the defect might be the result of chronic middle-ear infections in infancy: the brain never "hears" sounds clearly and so fails to

draw a sharp auditory map.) Short sounds such as "b" and "d" go by too fast—.04 second—to process. Unable to associate sounds with letters, the children develop reading problems.

The scientists drilled the 5- to 10-year-olds three hours a day with computer-produced sound that draws out short consonants, like an LP played too slow. The result: LLD children who were one to three years behind in language ability improved by a full two years after only four weeks. The improvement has lasted. The training, Merzenich suspect, redrew the wiring diagram in the children's auditory cortex to process fast sounds. Their reading problems vanished like the sounds of the letters that, before, they never heard.

Such neural rehab may be the ultimate payoff of the discovery that the experiences of life are etched in the bumps and squiggles of the brain. For now, it is enough to know that we are born with a world of potential—potential that will be realized only if it is tapped. And that is challenge enough.

With MARY HAGER

*Joseph Sparling and Isabelle Lewis (226 pages. Walker. \$8.95).

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