Assessments That Build Brain Cells

By Judy Willis, M.D., M.Ed.

Albert Einstein said, “Imagination is more important than knowledge.” Without imagination and investigation of ideas our collective fund of knowledge would languish. We do need assessments to determine what students learn and understand, but we can incorporate imagination in the creation of those assessments to insure that students’ creative thoughts and higher executive functions are incorporated into their assessment experiences.

Traditional and especially standardized tests assess only a few parameters such as rote memory, ability to follow instructions, organization, and time management. Testing that emphasizes those parameters gives students the message that those are the primary qualities of thinking inside the box that are valued most.

As functional neuroimaging has delved more into learning research, evidence is mounting about which brain activities are most associated with information processing and memory retention. Strategies to increase successful learning can be incorporated into the assessment process such that these go beyond passive reflections of student memory and recall and become active learning experiences that stimulate dendrite growth, neurotransmitter release, and efficiency of neuronal network communication.

For dynamic educators creative problem solving and critical analysis can be given the value they merit by being part of student assessment. The National Council of Teachers of English position paper “On Testing” that stated, “In light of continued and increasing efforts to undermine progress the profession has made toward authentic assessment of students’ real and vital engagement with language and literature, NCTE needs to reassert its repeated opposition to over-simplified and narrowly conceived tests of isolated skills and decontextualized knowledge. The crux of this concern has been the tension between the breadth of the English language arts curriculum and the restrictive influence of standardized means of assessing student learning.”

Assessment Over Time-From Macro to Micro

Yearlong Assessment: Although assessments ideally take place during each class period and lesson, planning the year’s major unit assessments while planning curriculum builds authenticity into those assessments. Starting the year with clear communication to students about the goals of their studies and expectations for their assessments sets a pattern that gives them the security that accompanies predictability.

Strategize from the start

- Gauge the assumptions students have about what is expected of them and how they will be assessed. This can be an open-ended discussion including their opinions about the purpose of assessments.
• When teacher expectations are accompanied by sincere acknowledgement that all students will be given the opportunity to be successful, regardless of what test scores and grades are in their records, they are inspired with self-confidence and lower anxiety.

• When teachers help students feel safe and in control of their potentials for success, they reduce affective filters and reduce the test-anxiety that may have lowered test performance in previous years.

• To insure that all students are aware of teacher expectations provide samples of A, B, C, and D student work from past years in a binder. The samples need to relate to assignments similar in character to theirs, but not be the same specific topics. In that way the students will have the opportunity to emulate quality and creativity, not content.

• Rubrics are powerful tools for promoting successful performance and predictable assessment.

Spot Errors in Comprehension With Daily Individual Assessments
This is where micro assessments and ongoing accountability are important for accurate student learning. Experienced teachers usually have some idea what their students’ grade ranges (and more importantly- their subject comprehension) are after the first several weeks of school. This is not because they frequently check their grade books, but because they assess student understanding during each lesson – sometimes more than once.

There is a fine line between the stress of calling on students when they are confused or uncomfortable speaking in front of the whole class and the need to frequently assess each student’s engagement and comprehension. There is also the need for students to feel comfortable asking for clarification so misinformation does not become stored in long-term memory.

Children who have lower academic expectations for themselves tend to ask for help less often. When you emphasize goals of individual self-improvement, effort, creative problem solving, and risk-taking, rather than competitive comparisons of student ability, students become more engaged and less threatened about participating. When students focus on how well they personally have improved rather than on comparing themselves to others they are more comfortable asking for help.

Embedding on-going assessment into everyday curriculum can be done by incorporating performance tasks into learning activities. Ways to keep students engaged, incorporate learning activities into assessments, and assure correct understanding while doing ongoing assessment include:

• Students are given cards with questions when they enter the classroom. The answers to their cards’ questions are posted on answer cards that label the seats or tables where they will sit that day. For example the card might say, “What state is the northern border of Oregon?” The student will search for the seat or table labeled “Washington.”

• Students simultaneously, at the count of three, hold up the colored or white side of an index card when the class is asked a yes/no or true/false question to signal their individual opinions.
• Students have white boards, erasable markers, and cloths (this often a treat for students). They write answers in a few large words or numbers in response to questions and hold them up simultaneously after being given adequate time for all to write answers. This gives instant teacher feedback as to who needs further explanation as well as keeping students engaged.
• When students are working independently or in small groups, teachers can move around the classroom listening to student discussions and assess what part of the material needs further explanation.
• Rather than have students store incorrect information consider having students stop worksheets or math problems done in class periodically and check answers that are posted (after they first show you the paper so you see that they did the work). If students know that they will be credited for corrected errors as well as for trying the work, they can mark the their errors in a different color and later show that they made corrections in a different color.
• Multiple answers: This assessment may take the form of asking several students for their answers to the same question even if the first student’s answer was correct. Similarly, once an answer is given students can raise hands if the agree or disagree.
• Summarizing is a valuable memory booster and a way to assess the day’s learning.
  ▪ Students write down what they think was the main point or concept of the lesson on note cards.
  ▪ The next day, the best cards are returned to the students who wrote them and they read them aloud (for class review) and post them on a bulletin board.
  ▪ Students who did not receive their note cards back will understand that the may have missed part of the critical point. It is their job to rewrite notes in their notebooks or journals after listening to classmates read the best ones aloud.
  ▪ If most of the students’ note card summaries are incorrect it is teacher feedback that the lesson may not have been as clearly communicated as intended and should be retaught in another way to reach the objectives.

When assessments are incorporated in daily instruction they become opportunities for both positive and corrective feedback and can keep all students engaged in the lessons. The addition of metacognition and post-assessment conferences will give students additional strategies to achieve success on standardized tests, and more importantly in their academic potential and positive educational experiences.

The best assessments will also prepare students for success in the careers where their generation will find opportunities. These assessments are the ones that correspond to
teaching that promotes creativity, analysis, judgment, expert thinking, and complex communication.

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NEURAL CONNECTIONS: Some You Use, Some You Lose

by JOHN T. BRUER

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JOHN T. BRUER is president of the James S. McDonnell Foundation, St. Louis. This article is adapted from his new book, The Myth of the First Three Years (Free Press, 1999), and is reprinted by arrangement with The Free Press, a division of Simon & Schuster Inc. ©1999, John T. Bruer.

OVER 20 YEARS AGO, neuroscientists discovered that humans and other animals experience a rapid increase in brain connectivity -- an exuberant burst of synapse formation -- early in development. They have studied this process most carefully in the brain's outer layer, or cortex, which is essentially our gray matter. In these studies, neuroscientists have documented that over our life spans the number of synapses per unit area or unit volume of cortical tissue changes, as does the number of synapses per neuron. Neuroscientists refer to the number of synapses per unit of cortical tissue as the brain's synaptic density. Over our lifetimes, our brain's synaptic density changes in an interesting, patterned way. This pattern of synaptic change and what it might mean is the first neurobiological strand of the Myth of the First Three Years. (The second strand of the Myth deals with the notion of critical periods, and the third takes up the matter of enriched, or complex, environments.)

Popular discussions of the new brain science trade heavily on what happens to synapses during infancy and childhood. Magazine articles often begin with colorful metaphors suggesting that what parents do with their infant has a powerful, lifelong impact on their baby's brain that determines the child's adult intelligence, temperament, and personality.

A Newsweek Special Edition tells us, Every lullaby, every giggle and peek-a-boo, triggers a crackling along his neural pathways, laying the groundwork for what could someday be a love of art or a talent for soccer or a gift for making and keeping friends.1 Also according to Newsweek, You hold your newborn so his skyblue 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 hand 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.2

Notice that these metaphors associate the neural cracking and zapping with rather mundane, commonplace activities -- giggling, peek-a-boo, playing with clothespins. This is appropriate. Brain science has not pointed to new ways of raising or teaching children that will really stimulate those synapses above and beyond what normal experiences provide. Thus the metaphors do properly convey that brain-based parenting amounts to doing no more than what most parents do normally.

In popular articles, the crackling and zapping metaphors are often followed by similes that provide accessible, colorful analogies of what goes on early in brain development. They tell us that, although some of the neurons in the newborn's brain are genetically hardwired at birth to control vital functions, like breathing and controlling body temperature, trillions and trillions of others are just waiting to be hooked up and played like orchestra instruments in a complex musical composition. Parents, educators, the babies' early experiences -- all these factors will determine which neurons connect and which connections will eventually wither and die from lack of use. Or to use a more technological image, infants' neurons are like the Pentium chips in a computer before the factory pre-loads 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 .... It is the experiences of childhood, determined by which neurons are used, that wire 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.

These metaphors and similes convey the image of infinitely modifiable infant brains. Neurons are in place awaiting the appropriate experiences and stimulation that will build synaptic connections among them. This figurative language -- and the picture it paints -- captures the popular understanding of early brain development and the understanding conveyed in the literature of the Myth of the First Three Years. We are left with the idea that infant brains are exuberantly growing and connecting in direct response to the actions of watchful singing, reading, and talking parents and caregivers.

But does this idea accurately capture what neuroscientists know about synapse formation early in brain development? How well does the neuroscientific evidence that the Mythmakers cite support this popular understanding?

**NEURONS, SYNAPSES, AND BRAIN DEVELOPMENT**

What happens to synapses during development, and why, are fundamental questions for modern neuroscience. As one prominent textbook, Eric Kandel and James Schwartz's Principles of Neural Science, says, Behavior depends on the formation of appropriate interconnections among neurons in the brain. Or as Patricia Goldman-Rakic, another neuroscientist who has conducted extensive research on primate brain development, puts it, The synaptic architecture of the cerebral cortex defines the limits of intellectual capacity, and the formation of appropriate synapses is the ultimate step in establishing these functional limits.

Neuroscientists do know that rapid synapse formation occurs early in the development of complex nervous systems, like those of cats, primates, and humans. Before we proceed to look at what neuroscience has learned about early, rapid synapse formation, we should first have a better idea of what developmental events precede it.

Neurons come in a variety of shapes and forms, but they all have a cell body that contains the cell nucleus. Most neurons have branches extending from the cell body. Axons, the long branches in the cells (usually enclosed in a myelin sheath), carry nerve impulses away from the cell body to other neurons. Dendrites,

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3 Debra Viadero, Brain Trust, Education Week, 18 September 1996, p. 31.
4 Begley, p. 55.
the shorter branches, generally receive never impulses from the axons of other neurons and transmit those impulses toward the cell body.

Usually, nerve cells are not in direct physical contact. There are microscopic gaps between the axons of one neuron and the dendrites of its neighbors. Communication between neurons takes place across these microscopic gaps or synapses. Chemical neurotransmitters move across the gaps from the presynaptic ending of the axon to the postsynaptic membrane of the adjoining dendrite. These chemical messengers then either excite or inhibit electrical activity in the postsynaptic cell. Via their synaptic connections, brain cells form the neural circuits that somehow support our sensory, motor, and cognitive skills and that ultimately regulate all of our behavior.

Neurons do not begin life in a mature state. They take time to develop. Neurons begin to form very early in fetal development. All our neurons derive from a single, thin layer of tissue in an embryonic structure called the neural tube. In humans, the first neurons that will eventually become part of the brain's cortical gray matter begin to appear at around 42 days after conception. During the next 120 days, around 120 days before birth, the full complement of our cortical neurons forms. The received neuroscientific view has been that we humans, along with our primate cousins, acquire all the cortical neurons we will ever have during roughly the middle third of gestation. (This view has been assumed in all the brain and early childhood literature, but recent research reported in October 1999 by Charles Gross and Elizabeth Gould is causing scientists to reconsider this assumption. Gross and Gould found that, in monkeys, newly formed neurons appear in the brain cortex continuously throughout the monkeys' lives.) When one considers that the human brain at birth contains on the order of 100 billion neurons, this means that during those 120 days, neurons form at a rate of around 580,000 per minute.

As cortical neurons form and the fetal brain grows, the neurons migrate from where they are first formed to their final position in the cortex. During this migration, neurons begin to grow axons and dendrites, the structures that will eventually allow them to form synapses and to build neural circuits.

The process by which axons reach their dendritic targets is not an arbitrary, random one. The brain has to form the correct contacts and circuits between axons and dendrites. Sometimes, the axons must traverse relatively vast distances -- on an axonal scale, distances equivalent to our making a coast-to-coast U.S. trip -- to find their appropriate target cells. Genetic mechanisms guide this neural mass migration. Following a trail blazed by physical, mechanical, and chemical markers, axons reach and identify their appropriate target cells. They even find the appropriate sites on the target cells' dendrites. In humans, the migration begins about four months before birth and ends shortly after birth. Once the axons and target cells recognize each other, synapses begin to form almost immediately.

In humans, synapse formation starts at around two months before birth and continues at least through the first year of life. The popular and policy interest in brain development begins at this point. It begins with considering what happens to synapses following birth, during infants' first three years of life.

SYNAPTIC DENSITY: COUNTING NEEDLES IN THE NEUROLOGICAL HAYSTACK

Neuroscientists discovered the period of rapid, postnatal synapse formation nearly 25 years ago. In these studies, scientists take samples of brain tissue from the same brain area of animals or humans that differ in age. In animal studies, the animals are sacrificed at different ages to obtain the tissue samples. In human studies, scientists must rely on samples of brain tissue taken at autopsy. This makes human studies a bit more difficult, because scientists are limited in the number of brains they can study and have little control over how many brains at each developmental age they can include in a study. In the animal and human samples, the scientists then count synapses, or structures associated with synapses, to see how synaptic
densities -- the number of synapses per unit area or unit volume of cortical tissue -- vary over the life span in a species.

Counting synapses in studies like these is the scientific equivalent of estimating the number of needles in a haystack, when both the number of needles and the size of the haystack are changing at constantly differing rates. This is not work for the timid, impulsive, or impatient. For a series of studies on rhesus monkeys done during the 1980s, Pasko Rakic and his colleagues at Yale University first used electron micrographs to enlarge the tissue specimens 14,000 times. They then counted the synapses in each of at least four specimens from dozens of animals. They counted over 500,000 synapses in 25,000 electron micrographs. From these counts, they calculated average synaptic densities.7

Calculating reliable densities also presents a series of needle-in-the-haystack methodological problems. Brains grow and undergo age-related changes, with different kinds of brain tissue growing at different rates -- neurons, nonneuronal brain cells, the space around cells, myelin sheaths on axons, and the number and size of blood vessels. Synapse counters must take account of and adjust for all these factors. They have to make reasoned assumptions to compensate for possible sampling errors, because there is no way they can count all the synapses in even one brain area. Scientists differ in how they choose to address these problems. These technological and methodological differences can complicate direct comparisons across studies and certainly across species.

This work is sufficiently demanding that relatively few scientists do it, and even fewer do it well. The result is that we have a relatively limited database -- much more limited than policy makers and the public are aware -- on synapse formation and synapse change over the life spans of species. As Patricia Goldman-Rakic reminded me, despite its importance for developmental neurobiology, this is a sparsely populated field. In fact one might say that the study of postnatal brain development is so sparsely populated that it does not really exist as a field of scientific inquiry at all.

In 1975, Brian Cragg first documented a phase of rapid increase in synapses, followed by a phase of synapse elimination in the visual area of the cat brain.8 In the cat, some synapse formation occurs before birth, but Cragg saw that there was a period of rapid synapse formation from eight to 37 days following birth. He observed peak synaptic densities at around the age of seven weeks in kittens. There followed a protracted pruning phase, during which synaptic densities and related neural measures decreased to adult levels. From the peak values, Cragg saw a 40% decrease in average synaptic density and a 29% decrease in the average number of synapses per neuron.

Two years later, Jennifer Lund and her colleagues reported a similar pattern in the development of the monkey visual cortex.9 They reported that synapses peaked at around eight weeks of age in the monkey. From eight weeks, but continuing through at least nine months of age, there was a gradual reduction until synapses stabilized at adult levels. From these early studies, neuroscientists concluded that, at least for the brain's visual area, there is an early developmental phase, during which the rate of synaptic formation


Although Cragg, Lund, and others documented this phenomenon, they were cautious in interpreting their discovery. Like archeologists who had just stumbled upon Stonehenge, they could describe their find in some detail but knew it would take more time and study to figure out what their discovery meant. Their studies assessed neither how changes in synaptic densities affected an animal's ability to see nor how synaptic change contributes to the functional maturation of the visual system.

They did raise an interesting idea that has remained part of neuroscientific theorizing but that has been largely lost in the popular discussion of brain development. They suggested that the loss of synaptic contacts might be an important and positive aspect of brain development. It is perhaps important to realize, Lund concluded, that the elimination of contacts may be as selective and constructive towards the final function of the visually altered neuron as the formation of specific synaptic contacts.10

By the 1980s, other researchers began to study the pattern and timing of synapse formation in monkeys and humans. Unlike Cragg's and Lund's initial studies, these later studies looked at various areas of the brain's cortex, not just the visual area. Some of the best work of this kind has been done on brain development in rhesus monkeys by Pasko Rakic, Patricia Goldman-Rakic, and their colleagues.11

The gestation period for rhesus monkeys is around 165 days, and the first cortical neurons form 40 days after conception. All the monkeys' neurons are formed over the next 60 days, and the process is complete 65 days before the monkeys are born. Rhesus monkeys (unlike humans) reach sexual maturity at age 3. In their studies, Rakic and his colleagues used animals that ranged in age from a few days postconception to mature 20-year-old adults.

In these animals, Rakic and his colleagues Jean-Pierre Bourgeois and Nada Zecevic examined developmental changes in synaptic densities in the visual area and three other brain areas: the somatosensory area involved in the sense of touch, the motor area involved in movement, and the prefrontal cortex involved in some memory tasks, planning, and other higher brain functions.

In all four areas of the monkey brain, they found the same general developmental pattern. First, there was a period of extraordinarily rapid increase in synaptic density. This period of rapid increase began two months prior to birth. At birth, infant monkeys' synaptic densities were approximately the same as the densities found in adult monkey brains. Synaptic densities continued to increase rapidly, reaching 2 months in all areas except the visual area, which peaked at 3 months. The peak densities were twice those seen in adult monkeys. Densities remained at this high plateau level until around age 3 years, the age of sexual maturity. At age 3, synaptic densities began to rapidly decrease, finally stabilizing at adult levels at age 4 to 5 years. The single exception to this pattern was the prefrontal area. There, rather than a rapid decline following the onset of puberty, there was a slight but significant decline in synaptic density starting at age 3 that continued throughout the monkeys' lives.

Further analysis of their data caused Rakic and his colleagues to conclude that decreases in synaptic density were due to genuine synapse elimination in the brain, not to the number of synapses remaining constant while the brain grew in volume. The rate of synaptic loss is staggering. In the monkey, over a

10 Ibid., p. 159.  
11 See Patricia S. Goldman-Rakic, Setting the Stage: Neural Development Before Birth, in S. Friedman, K. Klivington, and R. Peterson, eds., The Brain, Cognition, and Education (Orlando, Fla.: Academic Press, 1986), pp. 233-58; Rakic et al., Concurrent Overproduction of Synapses; and Rakic, Bourgeois, and Goldman-Rakic, Synaptic Development of the Cerebral Cortex.
period of 2 to 3 1/2 years, 2,500 synapses disappear every second from the primary visual area in each brain hemisphere.12

This research confirmed that a rapid increase followed by a decrease in synaptic density occurs throughout the rhesus monkey brain and is not confined to the visual area, as had been known since Lund's study.

The work of Peter Huttenlocher and his colleagues at the University of Chicago has revealed that a similar pattern occurs during human development, but on a different time scale. Of course this is no surprise, because monkeys and humans have very different life spans. Monkeys mature sexually at 3 years and are old at 20. Humans mature sexually early in their second decade and live another 60 to 70 years.

Over the past two decades, Huttenlocher's research group has been one of the very few that have studied changes in synaptic density over the human life span. They have counted synapses in around 50 human brains, looking at three brain areas. These brains were obtained at autopsy from patients ranging in age from 28-week-old fetuses to 90-year-old adults. Although 24 of the brains were from children in the prenatal-to-3-year age range, only three of the brains were from children between 4 and 11 years old, an important period in brain development for which we would like to have more data. Huttenlocher has reported results from three such studies in four research papers.13

In a 1979 paper, Huttenlocher reported results on changes in synaptic density over the life span in the frontal area of the human brain. He found that at birth infants have synaptic densities that are nearly the same as those found in adults. He found a rapid increase in synaptic densities between birth and age 1 year. Synaptic density peaked in the frontal cortex at around 1 to 2 years of age, when it was 50% higher than average adult values. Between the ages of 2 and 16 years, densities declined to mature levels and remained there throughout adulthood. Using data on changes in brain volume with age, Huttenlocher, like Rakic, argued that the decline in synaptic density could not be accounted for by a stable number of synapses confined within a growing brain. At age 7 years, the human brain has nearly reached adult volume, but synaptic density is still 36% higher than in adults. Thus the decreases in density must be due to a relative loss of synapses during development. He concluded: This finding confirms the fact that synaptic density in mammalian cerebral cortex declines late in development, after brain growth is nearly complete.14

In 1982 and 1987 publications, Huttenlocher reported changes in synaptic densities over the life span in the human visual cortex. Again, at birth, synaptic densities in this brain area were near adult levels. Densities increased most rapidly between 2 and 4 months of age and peaked between 8 and 12 months of age at levels 60% higher than those seen in adult. In the visual area, there was then a longer period of decreasing density extending beyond 3 years of age, stabilizing at adult levels at around age 11.

In his most recent published study, Huttenlocher looked at two brain areas -- the frontal cortex (the same area studied in the 1979 paper) and the auditory cortex -- in the same human brains. He found that synaptic density peaked in the auditory cortex at around 3 months of age, but that it did not peak in the frontal area


14 Huttenlocher, p. 201.
until around 3 1/2 years, a later peak than he had found in his 1979 study. This suggested to him that synaptic development in the frontal area lags behind that in the auditory area. Synapse elimination also appeared to be on different timetables in the two areas. Synapse elimination appeared to be complete by age 12 years in the auditory cortex, but it continued in the frontal area until mid-adolescence. Huttenlocher did point out, however, that his conclusions on rate of elimination were only tentative because he had only four adolescent brains in the study, and these showed considerable variability.

The Rakic and Huttenlocher data figure prominently in developmental neuroscience and in the early childhood literature because they present the best direct evidence we have in humans and nonhuman primates on how synaptic densities change over the life span. As I noted, methodological and technical problems can make precise comparisons between studies and across species problematic, yet the research points to striking similarities between rhesus monkeys and humans. First, in both species, synaptic densities peak at around the same absolute level in all brain areas, and final, mature synaptic densities are around 60% of the peak values in all brain areas that have been studied. This suggests, as Rakic and Huttenlocher have pointed out, that there might be a normal range for synaptic density throughout the primate brain. Having either too few or too many synapses might be detrimental to brain function.

The studies also show that in both species there is a three-stage pattern of change in synaptic densities over the life span. What we see from the research is that synaptic densities follow an inverted-U pattern over our lifetimes, as they do over the life span of rhesus monkeys. At birth, we have approximately the same synaptic densities in our cortex that we do as adults. Rapid synapse formation following birth leads to a plateau period during which synaptic densities exceed adult densities. Synapse elimination beginning at puberty reduces densities to adult levels. It will be helpful to keep this inverted-U image in mind as we begin to consider how neuroscientists and Myth advocates interpret what this pattern might mean for behavior, intelligence, and learning.

PET SCANS AND SYNAPTIC DEVELOPMENT

In humans, we also have some indirect evidence that synaptic densities in the brain vary over the life span. A 1987 positron emission tomography (PET) study by Harry Chugani, M.E. Phelps, and J. C. Mazziotta provides this indirect evidence that corroborates Huttenlocher's more direct evidence.15

Brain imaging technologies, like PET, allow neuroscientists to monitor brain activity in living human subjects. PET studies use radioactively labeled oxygen and glucose to measure rates of brain energy metabolism. In human studies, scientists inject these substances into experimental subjects. The blood supply delivers the substances to the brain. The scientists assume that the more active brain areas would require more energy and would use more of the radioactively labeled, energy-providing substances. After a period of time, the labeled substances undergo radioactive decay and emit positrons. (Positrons are subatomic particles that have the same mass as an electron but that, unlike electrons, carry a positive rather than a negative electrical charge.) Positron detectors arranged in a ring around the subject's head detect these emissions and -- using some geometry, some physics, and some high-powered computing -- scientists can calculate the paths that the positrons traveled. The path data allow scientists to construct images that show which areas of the brain are burning more or less of the oxygen or glucose in response to energy demands.

In their oft-cited work, Chugani and his colleagues report results of PET scans on 29 epileptic children, ranging in age from 5 days to 15 years. These children needed PET scans for diagnostic purposes, so in one

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sense the children were not totally normal neurologically. We have no PET data (at least none that I have been able to find) from normal children, because PET scans require the injection of radioactive substances that researchers cannot administer to normal, healthy children. Chugani and his colleagues to address this issue, arguing that apart from their epilepsy, the children were otherwise neurologically sound. The researchers compared the epileptic children's scans to those taken on seven young, normal adults, ranging in age from 19 to 30.

In this study, the scientists gave the children radioactively labeled glucose and measured the rate at which specific brain areas took up the glucose. While the scans were being acquired, the scientists made every effort to eliminate, or at least minimize, all sensory stimulation for the subjects. Thus they measured the rate of glucose uptake when the brain was (presumably) not engaged in any sensory or cognitive processing. That is, they measured resting-brain glucose metabolism.

Despite this study’s popularity and importance, it is a single study of just 29 epileptic children, many of whom had been medicated since infancy and 18 of whom had received medication on the day they were scanned. However, it provides almost the only imaging data that we have from which to make guarded inferences about what might happen during normal human brain development.

With these cautions in mind, what did Chugani and his colleagues find? They saw that, during the first year of life, glucose uptake in the infant cortex was between 65% and 85% (depending on the specific brain area) of that found in adult brains. In newborns, the area with the highest metabolic activity was the primary sensorimotor area, the area that supports the infants' sense of touch and bodily sensation. During the second and third months of development, there was a gradual increase in resting metabolic activity in other brain areas, such as those associated with hearing and vision. By age 8 months, metabolic activity began to increase in some frontal areas of the brain. At age 1 year, the anatomical distribution of glucose uptake in infants' brains had the same qualitative pattern as that found in adult brains. However, the infant rates were still quantitatively lower than the adult rates.

After the first year, the maturational curves for all brain areas followed a similar pattern. In all the areas examined, metabolic levels reached adult values when children were approximately 2 years old and continued to increase, reaching rates twice the adult level by the age of 3 or 4. Metabolic levels remained at this high plateau level until children were around 9 years old. At age 9, rates of brain glucose metabolism started to decline and stabilized at adult values by the end of the teenage years. Like the synaptic densities Rakic and Huttenlocher calculated, rates of brain glucose metabolism follow an inverted-U pattern from birth to early adulthood.

Huttenlocher counted synapses, where-as Chugani and his colleagues measured glucose metabolism. To connect glucose metabolism to synapses, Chugani and his colleagues reasoned as follows. First, based on Rakic and Huttenlocher's work, we know that, in rhesus monkeys and humans, there is initially a vast overproduction of synapses, followed by synaptic loss that continues until early adolescence. What Chugani and his colleagues see in the PET scans, they argue, is consistent with the process of synaptic overproduction and elimination. They cite other evidence to show that synapses and dendrites account for most of the glucose the brain consumes. So, they reason, as the density and number of synapses and their associated neural processes wax and wane, so too does the rate of brain glucose metabolism. Thus what Chugani and his colleagues measured provides an indirect measure of what Huttenlocher counted. Changes in measures of glucose metabolism over time are correlated with changes in synaptic density and numbers over time. Chugani and his colleagues also note that there might be other explanations for the pattern they observed.

Chugani's 1987 PET study is one of the all-time favorites in the Myth literature. It is one of those all things to all people studies and possibly one of the most over-interpreted scientific papers of the last 25 years.

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Part of the reason for this is our fascination with brain images. Imaging studies have assumed a central but problematic role in how the public understands the brain.

We are fascinated and mystified by how the brain functions. But until recently we have not been able to see a living, functioning human brain in action. Vividly colored pictures that purport to show the brain actually perking or bubbling along give us concrete images of what before we had thought of as hidden and mysterious processes. Before brain imaging, the brain was indeed a black box for most of us.

We should not forget, however, that PET images of a brain are not Polaroids. They are images that represent complex data after considerable statistical processing and enhancement. Our brains are not red when we look at an intense black-and-white checkerboard and blue when we close our eyes. The colors represent increases and decreases in brain metabolism or cerebral blood flow over some baseline level. Far from being Polaroids, brain images are difficult to acquire and even more difficult to interpret, even for the experts.

Nonetheless, Chugani's PET study is taken as the paradigmatic example of how neuroscience is now providing hard data about the importance of the first three years of life.

According to Starting Points, new neuroscientific research showing that the brain development that takes place before age one is more rapid and extensive than we previously realized underscores the importance of the first three years of life. The report cites Chugani's study as evidence for this claim.16

Rethinking the Brain further elaborates on the significance of this imaging study, emphasizing the changes in the brain's metabolic activity during the first year of life: Cortical activity rises sharply between the second and third months of life — a prime time for providing visual and auditory stimulation. By about eight months, the frontal cortex shows increased metabolic activity. This part of the brain is associated with the ability to regulate and express emotion, as well as to think and to plan, and it becomes the site of frenetic activity just at the moment that babies make dramatic leaps in self-regulation and strengthen their attachment to their primary caregivers.17 This is the period, according to Rethinking, when parents and caregivers can most help infants develop self-regulatory skills.

The interpretations of Chugani's PET study that these policy documents offer are, to be kind, highly convoluted and go well beyond the evidence presented in the original scientific paper.

Let's just consider the passage quoted from Rethinking the Brain. If you look at the published data, it is not the case that cortical activity rises sharply between the second and third months of life. It is more accurate to say, as Chugani does, that one can observe increases in glucose metabolism in various cortical areas at that time. Where there was at 2 months of age very low metabolic activity in the cortex, at 3 months, there is more metabolic activity -- nothing so dramatic as a sharp rise. Similarly, the frontal cortex is not frenetic at 8 months; rather, its rate of metabolic activity increases to levels comparable to other brain areas. One might say it begins to come online at 8 months. It is not clear what the rationale is for thinking that the PET results give reasons for providing visual and auditory stimuli at age 2 months and self-regulatory training at 8 months. Although the frontal cortex might come online at 8 months, it will not mature, at the synaptic level, until puberty, no matter what kind of stimulation a parent might provide.


A PET study showing when brain areas come online metabolically or a neuroanatomical study that shows when synaptic densities increase does not speak to when, or even to whether, parents might be able to train brain areas. The simple fact is that, although we know these events occur, we do not know what they mean for child development or to what extent, if at all, environmental and parental stimulation affects these events.

More interesting, however, is that Chugani and his colleagues do not interpret their PET study as indicating that birth to age 3 is the most important period for parents and caretakers to have an impact on brain development. In their original paper, they conclude that our findings support the commonly accepted view that brain maturation in humans proceeds at least into the second decade of life. For Chugani, however, it is the plateau period of high metabolic activity and high synaptic connectivity -- the years from 3 to 8 or 9 - - that is most significant developmentally. It is during this developmental period, Chugani consistently claims, that experience fine-tunes neuronal circuits and makes each individual's neuronal architecture unique. Of course, this too is an interpretation that goes beyond the data he presents in the PET study.

What we must always keep in mind is that this PET study is important because it corroborates, using indirect evidence, the existence of the inverted-U pattern that Huttenlocher documented with more direct evidence based on counting synapses. What that pattern might mean for child development and parenting is a substantive, difficult question that is not adequately addressed in either Chugani's original article or in the discussions of early synapse formation in documents like Starting Points and Rethinking the Brain. What might current neuroscience contribute to answering this question?

DIGGING BENEATH THE METAPHORS: NEUROSCIENCE, THE MYTH, AND SYNAPSE FORMATION

The neuroscience we have just reviewed plays a fundamental role in the Myth literature. Policy and popular descriptions convey this neuroscience via the neural crackling and zapping metaphors that link early brain development, particularly rapid synapse formation, with the amount and quality of stimulation infants receive during their first years of life. Now that we have a better understanding of what the relevant neuroscience says, we can better assess the extent to which the science supports the ideas and images that the Myth conveys about early brain development. Three Myth claims in particular are based on the phenomenon of early, rapid synapse formation, which is the Myth's first strand.

First, the Myth literature maintains that this period in development is crucial because it is the time during which most synapses form and that the more synapses we have, the more intelligent we are. One often sees claims in the popular birth-to-3 articles that more synapses mean more brainpower. The Myth suggests that the reason why we should talk, sing, and read to an infant is to stimulate the baby's brain, thereby facilitating synaptic growth. This increases the infant's brainpower, thus building a better brain than the baby would have otherwise. More synapses are better than fewer. The evidence indicates, we read, that the more connections you have, the smarter you are.

Second, there is a claim that early environmental stimulation causes synapses to form. According to the Education Commission of the States, the early years are developmentally crucial because brain connections

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18 Chugani, Phelps, and Mazziotta, p. 496.
develop especially fast in the first three years of life in response to stimuli, such as someone talking to, singing to, reading to, or playing with the infant or toddler. In It Takes a Village, we are told that with proper stimulation brain synapses will form at a rapid pace, reaching adult levels by the age of two and far surpassing them in the next several years. And according to Inside the Brain, Growing evidence indicates that early mental stimulation promotes the growth of synaptic connections between brain cells. Another article tells us that the more experience or stimulation that an infant undergoes, the more brain connections are made.

Third, there is a claim that the period of rapid synapse formation is the time during which basic learning skills are hardwired and that somehow this process ends when the period of rapid synapse formation ends. Joan Beck, the Chicago Tribune columnist, tells us that, during the first three years of life, the brain grows most rapidly and then becomes hard-wired into an organ of thinking. What happens, she concludes, during the first three years -- the time of rapid synapse formation, the only time we have to build a better brain -- affects the child for the rest of its life.

Let's look at each of these claims individually.

NEURAL ACCOUNTING: BRAINPOWER AND SYNAPTIC DENSITY

The Myth propagates a profound misconception about the relation between synapses and brainpower and what neuroscientists know about that relation. The misconception is that there is a linear relation between the number of synapses in the brain and brainpower or intelligence. More simply, the Myth literature suggests that more synapses equal more brainpower. This misconception contributes both to the popular appeal of the Myth. It allows us to think about brain development and intelligence in a concrete, quantifiable way. We come to believe that we can measure our success as parents, care-givers, or teachers by doing a little neural reckoning. Seductive as this view might be, the neuroscientific evidence we have does not support it. Whatever the relation is between synapses and brainpower, it is not a simple one.

The neuroscientific findings on humans and animals show, as we have seen, that synaptic density follows the inverted-U pattern -- roughly, low, high, low -- from birth through childhood to adulthood. However, none of the studies looked at whether monkeys or humans with more synapses or with higher resting rates of brain metabolism were smarter. Data like Rakic's, Huttenlocher's, and Chugani's do not speak to this issue at all, and there are no reliable data that do.

However, there have been a few cases in which researchers have studied defective brains. People suffering from the genetic disorders that cause Down's syndrome or Patau's syndrome do have brains with


23 1997 Education Agenda/Priorities.
abnormally low synaptic densities. As early as 1975, however, neuroscientists also had found cases of human mental deficiency in which the patients' brains had abnormally high synaptic densities. 25

More recently, Huttenlocher reported a case of a mentally defective child whose brain had synaptic densities higher than those found in normal patients. 26 He speculated that patients whose brains had undergone developmental arrest at an early age would likely have abnormally high synaptic densities as adults and not be the better off for it. Again, following the theme first enunciated by Lund in the mid-1970s, synaptic loss is fundamental to normal brain development. At the synaptic level, normal brain development may be a regressive, rather than a progressive, process. Creating more synapses or preserving as many of them as we can into adulthood may be neither possible nor desirable. Although the phrase use them or lose them is a popular one in discussing synapses and the brain, it gives a misleading overall description of what goes on during normal brain development. It tends to conceal the fact that losing synapses is also part of the maturation process for our brain circuitry and that such loss is normal, inevitable, and beneficial. 27

Recent research on fragile-X syndrome also suggests that too many synapses are detrimental rather than beneficial to efficient mental functioning. Fragile-X syndrome is the second most common form of mental retardation in humans after Down's syndrome. It affects approximately one in 2,000 males and causes severe mental and behavioral impairments. Mature brain tissue removed from fragile-X patients at autopsy contains long, thin, twisted post-synaptic spines that resemble the spines seen during early brain development. Synaptic densities are also higher than normal in these tissue samples. Scientists have constructed an animal model of fragile-X in a strain of genetically altered mice. Brain tissue removed from these mice shows the same twisted dendrite structures and higher than normal synaptic densities that are found in the human samples. In adulthood, fragile-X mice have more synapses than do normal mice. Fragile-X syndrome may result from a developmental failure that prevents synaptic maturation and proper synapse elimination during development. With fragile-X, more is indeed less. 28

One final, commonsense reflection on the inverted-U pattern should convince us all that more synapses do not necessarily mean more brainpower. Synaptic densities follow an inverted-U pattern, but our intellectual capacities and ability to learn do not. At birth and in early adulthood, synaptic densities are approximately the same. However, by any measure one cares to use, adults are more intelligent, have more highly flexible behaviors, and show capacities to learn subject matter and reasoning skills that we do not see in infants, toddlers, and 3-year-olds. Furthermore, the late adolescent and early adult periods of rapid synaptic loss do not result in a drop in brainpower. Despite what many parents might express about the difficulties of having teenagers in the house, the problem that parents confront is not that their teenagers become rapidly less intelligent as they leave junior high school and enter high school. They may be emotionally and temperamentally difficult, but as massive synapse elimination begins at puberty, adolescents are just beginning a stage in their lives during which they have the ability to learn and master diverse, complex, and abstract bodies of knowledge. Based on observed behavior, measures of intelligence, and our ability to learn, there is no clear connection between synaptic densities or synaptic numbers and brainpower.

25 Cragg, op cit.

26 Huttenlocher and Dabholkar, op. cit.


Goldman-Rakic summarized what she and many brain scientists believe, given the evidence they currently possess, about the relation between early synapse formation, learning, and intelligence. As she told the participants at a Denver meeting sponsored by the Education Commission of the States: While children's brains acquire a tremendous amount of information during the early years, most learning takes place after synaptic formation stabilizes. From the time a child enters first grade, through high school, college, and beyond, there is little change in the number of synapses. It is during the time when no, or little, synapse formation occurs that most learning takes place.

While neuroscientists believe that there is some relation between brain connections and intellect, they are still trying to discover what that relation might be. Based on their studies of synapse formation and elimination in nonhuman primates and in humans, neuroscientists like Huttenlocher and the Rakics draw a cautionary conclusion. In a 1986 article, Goldman-Rakic wrote, Although neuroscientists believe that the ultimate explanations of behavioral phenomena will come from an understanding of cell-to-cell communication at the synaptic level, at the same time, no one believes that there will be a simple and linear relationship between any given dimension of neural development and functional competence. That is, despite what we read in the papers, the neuroscientific evidence does not support the claim that the more connections you have, the smarter you are.

MAKING SYNAPSES GROW: STIMULATION AND EARLY BRAIN DEVELOPMENT

The Myth literature also conveys a misconception that early environmental stimulation or experience causes synapses to form. This, too, runs counter to the existing neuroscientific evidence. Rather, the research suggests that genetic and developmental programs, not environmental input, control early synapse formation.

Data from several species, including humans, show that environmental input does not initiate rapid synapse formation. Rapid synapse formation begins in the visual cortex of a rat about two days after birth and increases rapidly until the rat is around 3 weeks old. However, rats do not open their eyes until they are around 2 weeks old, long after the rapid growth is well under way. Rapid synapse formation begins before the animals have any sensory stimulation from their environments. In the monkey visual cortex, as we have seen, rapid synapse formation begins two months prior to birth. According to Huttenlocher's data, synapse formation also begins in some areas of the human brain before birth. If in these species rapid synapse formation begins before the animals have any sensory input from the environment, then sensory input does not initiate rapid synapse formation.

Furthermore, following birth, environmental input does not appear to drive the process of rapid synapse formation, to cause more synapses to form. Of necessity, evidence for this claim comes from studies done on monkeys.

Somatosensory, or tactile, skills in rhesus monkeys appear very early in their development. At around 2 months, rhesus infants can make tactile discriminations of size and texture with the same precision as adults. This is also the age, based on the Rakic data, at which synaptic densities peak in the monkey somatosensory cortex. Neuroscientists take this correlation as suggesting that, when synaptic densities peak, a critical mass of synapses forms. This critical mass of connections allows brain circuits to come online, thus allowing the monkey to make the tactile discriminations.

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29 Bridging the Gap Between Neuroscience and Education: Summary of a Workshop Cosponsored by the Education Commission of the States and the Charles A. Dana Foundation (Denver: Education Commission of the States, 1996), p. 11.
30 Goldman-Rakic, p. 234.
In one experiment, Mary Carlson raised an infant monkey with its right hand restrained in a soft leather mitten.\textsuperscript{31} The mitten kept the monkey's hand in a tightly fist position from birth until the animal was over 4 months of age. During that time, the animal received no sensory stimulation to its right hand. Carlson expected that this extended sensory deprivation would retard the animal's ability to make size and texture discriminations. When the mitten was removed, the animal showed some initial, transient impairment, but, to Carlson's surprise, the monkey quickly began to perform at the same levels as normal animals. If a critical mass of synapses is necessary to perform this task, then the monkey possessed that critical mass. It had tactile skills comparable to normally reared animals. Yet the animal's right hand had not received any sensory stimulation for the first four months of its life nor had the part of the brain that would process those stimuli. Therefore, for the tactile system at least, it is not true that stimulation causes synapses to form. The synapses formed in the absence of any stimulation.

A few studies have examined the effects of both sensory deprivation and increased sensory input on the rate of synapse formation and on synaptic density in rhesus monkeys. In the deprivation experiment, researchers removed the retinas from fetal rhesus monkeys during the first half of gestation, around 80 days before the monkeys would normally be born.\textsuperscript{32} After the monkeys were born, they compared the visual areas of these totally deprived animals' brains with the visual areas of normal, age-matched monkeys. There were some differences. The blind animals had fewer neurons going into their brains' visual areas than the sighted animals, and for that reason, blind animals had smaller visual areas than the sighted animals. However, despite the fact that the experimental animals had been totally deprived of any visual stimulation, there were no significant differences in synaptic densities between the blind and the sighted monkeys. The rate and extent of synapse formation were the same in blind and sighted animals of the same age.

In the increased sensory stimulation experiment, three-week-premature rhesus monkeys received intensive visual stimulation from birth to see if such stimulation could accelerate synapse growth in their visual areas.\textsuperscript{33} This experiment directly tested the claim that the more experience or stimulation an infant undergoes, the more brain connections are made. Contrary to the experimenters' expectations, despite all the extra stimulation, the synaptic densities of the preterm, highly stimulated monkeys were no different from those of the full-term, normally stimulated control monkeys.

Together, experiments like these show that the rate of synapse formation and the degree of synaptic density are impervious to the quantity of stimulation -- either to deprivation or to overstimulation. Contrary to what the Myth suggests, early rapid synapse formation appears to be under genetic, not environmental, control. This was clearly stated in one of the most recent scientific reviews of the relation between synaptic change and mental development: The developmental accumulation of synapses [i.e., the phase of early rapid increases in synaptic density] is altered much less by environmental stimulation than has been appreciated or would be expected by conventional wisdom.\textsuperscript{34}


\textsuperscript{34} Goldman-Rakic, Bourgeois, and Rakic, p. 38.
RAPID SYNAPSE FORMATION AND HARDWIRING THE BRAIN

Finally, let's consider the claim of the Myth's supporters that it is only during the early years of life that we have the opportunity to build better brains. The Myth suggests that after the period of rapid synapse formation ends -- a period that, based on Huttenlocher's data, ends in the human brain at around 3 to 3 1/2 years of age -- the mechanisms for learning are established, and brain circuits become hardwired. To adequately assess this claim, we will have to look at how behaviors and abilities change during and after the period of rapid increase in synaptic densities.

One of the best examples to consider in assessing this claim comes from a series of studies done by Goldman-Rakic and Adele Diamond, a developmental psychologist. These studies examined how short-term, or working, memory skills develop over the early months of life in both infant monkeys and human infants. Specifically, the researchers studied how monkeys and infants improved on what psychologists call delayed-response tasks.35

In delayed-response tasks, the experimental subject observes the experimenter hide an object or morsel of food in one of two wells on a tray. The experimenter then obscures the tray from the subject's view for a period of time. After the delay, the subject selects one of the two locations. The task requires that the monkeys or infants remember information about where the object was hidden for a period of time (the delay) and then find the object when the only information available to guide the choice is their memory of where the experimenter had hidden the object. To do this, the infant monkey or human must have a mental representation, or a memory trace, of the original hiding and the ability to hold that memory online during the delay.

Such simple tasks tap into a highly significant mental skill. Delayed-response tasks measure the emergence of representational memory -- the ability to create and maintain a mental representation of an event that is no longer present to the senses. Representational memory is a building block, if not cornerstone, of cognitive development in man, according to Goldman-Rakic.36 Furthermore, there are abundant neuroscientific studies, using a variety of techniques and measures, that provide strong converging evidence that this building block of cognitive development is dependent upon a specific part of the monkey brain, the dorsolateral prefrontal cortex. The association between this brain area and the ability to do delayed-response memory tasks is one of the best-established brain/behavior relations in neuroscience. This allows us to compare improvement on delayed-response tasks with changes in frontal brain areas. It allows us to understand how improved representational memory corresponds with changes in synaptic density.

Goldman-Rakic and Diamond regularly tested monkeys and infants on delayed-response tasks, starting when the monkeys or babies could first make reaching movements. When the monkeys were 1 1/2 months old (the age at which the monkeys could first make reaching motions at the tray), the experimenters began testing them on delayed-response tasks five days per week. Testing continued until the monkeys were around 4 months old. The mark of success on delayed-response memory tasks is the length of delay the


animal or infant can tolerate before starting to make incorrect choices. The longer the delay tolerated, the better the ability to hold information online in memory to guide the choice.

Infant monkeys first showed an ability to succeed at delayed-response tasks when they were a little less than 2 months of age, tolerating delays of around 2 seconds. By age 2 1/2 months, they could tolerate delays of 5 seconds and by age 4 months, delays of up to 10 seconds. The young monkeys showed a gradual, constant developmental improvement on these tasks, improving at a rate of around 1 second per week in the delays they could withstand.

Although Diamond and Goldman-Rakic did not count synapses in these monkeys, one can relate the improvement on the memory tasks to the developmental changes that Rakic and his colleagues found in their studies of frontal areas in the monkey brain. Remember that they found that synaptic density peaks in all areas of the monkey brain at around 2 months. This is precisely the time at which the monkeys began to show their first successes on delayed-response tasks. This suggested to Goldman-Rakic that the first appearance of basic skills and abilities associated with a brain area occurs when synaptic densities, as measured by Rakic, peak in that brain area. Here the ability to form representational memories in monkeys is correlated with the peaking of synaptic monkey brains. The pattern seems to be that synaptic densities increase under genetic control, and, when they peak, the associated skills and behaviors first appear in elementary form.

We can tell the same, although a bit more complicated, story about the emergence of representational memory in human infants. Diamond tested infants on delayed-response tasks every two weeks starting at around 6 months (the age at which babies could first make reaching movements toward the tray). She tested the infants once every two weeks until they were 12 months old. Infants first started to succeed at delayed-response tasks at delays of up to 2 seconds when they were around 7 months of age. The infants improved on the tasks at a rate of about 2 seconds per month, until at age 1 year, they could tolerate delays of up to 10 seconds. What happens to the monkey's representational memory abilities between 2 and 4 months of age occurs in the human infant over the period of 7 to 12 months.

Using Huttenlocher's data, we can also relate improvements in the infants' representational memory abilities to development of the frontal areas in the human brain during the second half-year of life. However, to compare accurately the monkey and human data, we must first deal with one complication. Earlier, I mentioned that neuroscientists differ in the assumptions and methods they use to calculate synaptic densities and that this can complicate direct comparisons across studies and across species. This is true for the Rakic and Huttenlocher studies.

In his human studies, Huttenlocher computed the number of synapses per unit of whole cortical tissue, including the neural tissue as well as blood vessels, glial cells, and nonneuronal cells and spaces. In the monkey studies, Rakic computed synapses per unit of neuropil — that is, whole cortical tissue, less blood vessels, glial cells, and nonneuronal cells and spaces. Thus Rakic and Huttenlocher used different denominators in computing densities. Different denominators matter because the different kinds of brain tissue included in the denominator grow at different rates during development.

Using his original whole brain tissue denominator, Huttenlocher found that synaptic densities peaked in the frontal areas of the human brain at around 3 years of age. However, when he recomputed his data for the frontal area using neuropil as the denominator (thus making his data more readily comparable to those of Rakic), he found that synaptic density peaked in the frontal area of the human brain at around 7 months of age.\footnote{Huttenlocher and Dabholkar, op. cit.} Goldman-Rakic and Diamond found that 7 months is the age at which human infants can first
reliably succeed at delayed-response tasks. Thus, in both infant monkeys and human infants, representational memory abilities first appear when the number of synapses per unit of neuropil in the associated brain area reaches peak value.

The Diamond and Goldman-Rakic studies also provide some additional insight into how experience contributes to improved representational memory skills. In addition to the group of infants that they tested biweekly, they had another group of infants, ranging in age from 2 months to 12 months. They tested each of these infants only once on a delayed-response memory test. This allowed them to determine if improvement on the memory task might be due to practice. It allows us to consider whether experience or increased stimulation affects the development of basic representational memory.

Diamond and Goldman-Rakic found that there was no difference in performance on delayed-response tasks between 9-month-old infants tested once at that age and 9-month-old infants who had been tested every two weeks. That is, infants who had already been tested at least 10 times by age 9 months did no better than 9-month-old infants doing the task for the first time. They also found that the same rate of improvement -- about 2 seconds per month in delays tolerated -- occurred in infants from all social classes.

In a later study, Diamond did find that over a variety of ages, infants who were repeatedly tested could tolerate delays 1 1/2 to 2 seconds longer than infants of the same age who had been tested only once. However, she also found that the advantage for the repeatedly tested infants disappeared by the time the infants were 12 months old. Together these findings suggest that representational memory develops at approximately the same rate independent of practice or exposure to the task and independent of any class-related differences in early childhood experience.

When neuroscientists attempt to interpret their findings on rapid synaptic development in behavioral terms, they tend to list examples that exactly parallel the case of representational memory. In monkeys, synaptic density peaks in all cortical areas between 2 and 3 months of age. At around 2 months of age, infant monkeys can make precise tactile discriminations of size and texture (a sensorimotor function). They begin to visually track small objects, reach for objects guided by vision, and visually discriminate objects (visual functions). They show some ability to use individual fingers independently (a motor function). So, the argument goes, in the monkey, all these behaviors emerge between 2 and 3 months of age, at exactly the time when synaptic densities peak throughout monkeys' brains. In interpreting the human data, neuroscientists such as Huttenlocher and Chugani allude to the correlations between synapse change and behavior found in monkeys. Then they argue by analogy that the same is probably true for infant humans, citing a few additional examples of language development that are unique to humans.

Neuroscientists also generally agree that this relationship between first appearance of a skill and peak synaptic density is only a part of the story. Skills continue to improve and behaviors continue to become more sophisticated long after rapid synapse formation ceases and well into the synaptic plateau period. Sensory, motor, visual, and memory skills continue to develop in the monkey, some reaching mature levels only at sexual maturity, when synaptic densities start to decline. The same is true for humans. Among primates, both humans and monkeys, childhood and adolescence -- the plateau period for synaptic densities -- is a time of massive learning and rapid behavioral change, when adult-level skills emerge in language, mathematics, and logic. On delayed-response tasks, adult monkeys can tolerate delays of two minutes or more. Adolescent children and adults are able to tolerate delays of hours if not days, in addition to developing other sophisticated representational memory skills. The circuitry we need to do these things is not complete, hardwired, or permanently fixed during early development. It is not limited to the time when synapses form most rapidly.
THE SYNAPTIC PRESERVATION STRATEGY

There is one other subtle wrinkle about early synapse development that I should address. According to Huttenlocher's data, the period of rapid synapse formation in the young human brain appears to end at around 3 years of age. The neuroscientific data suggest that environmental stimulation neither initiates this process nor causes more synapses to form. However, this leaves open the possibility that early experience might strengthen existing synapses and that these strengthened synapses would be more likely to survive through the high-plateau period and into adulthood. In this view, building better brains is best accomplished via an aggressive synaptic preservation strategy. We talk, sing, and read to babies to save synapses from elimination, not to cause synapses to form in the first place. In some of the early childhood discussions, we read that the brain ruthlessly prunes synapses that have received inadequate stimulation prior to puberty. This line of reasoning suggests that building optimal brains requires that we use as many synapses as possible before puberty or lose them for sure afterward. The more you use, the fewer you will lose.

Chugani has both offered and encouraged this interpretation of his PET study. According to a Wayne State University article on his work, The trick ... is to keep desired connections alive and permanent to allow for efficient processing of a variety of functions. In an academic review of his own work, Chugani wrote, The individual is given the opportunity to retain and increase the efficiency of connections that, through repeated use during a critical period, are deemed to be important, whereas connections that are used to a lesser extent are more susceptible to being eliminated.

Rethinking the Brain makes the same argument:

As pruning accelerates in the second decade of life, those synapses that have been reinforced by virtue of repeated experience tend to become permanent; the synapses that were not used often enough in the early years tend to be eliminated. In this way, experiences -- positive or negative -- that young children have in the first years of life influence how their brains will be wired as adults.

Thus the strategy for optimal brain development is to stimulate as many synapses and circuits as much as possible during the period of high connectivity in order to mitigate the effects of the imminent, ruthless pruning at puberty. So, the argument goes, we should engage in an aggressive program of synaptic conservation with our children. We should provide experiences and environments that promote, as the Bee Gees might describe it, neural staying alive.

Superficially, this strategy makes sense, but there is no neuroscientific evidence to support it. First, neuroscientists have little idea how experience before puberty affects either the timing or the extent of synaptic pruning. Scientists -- Rakic, Goldman-Rakic, and Huttenlocher among them -- have documented that pruning does occur at puberty. None of the studies we have, however, compared differences in final adult synaptic densities with differences in an individual's experiences before puberty. Neuroscientists do not know, for monkeys or humans, whether early experience increases or decreases synaptic densities or synaptic numbers after puberty. They do not know if prior training and education affect either loss or retention of synapses at puberty. They do not know what kinds of synapses -- excitatory versus inhibitory -- are selectively pruned. Nor do they know whether the animals with greater densities in adulthood (pathological conditions like fragile-X syndrome aside) are necessarily more intelligent and developed.

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40 Shore, p. 20.
Some neuroscientists are frankly puzzled about this synaptic preservation strategy. When I asked Bill Greenough about the soundness of such a strategy, he replied, The evidence strongly suggests that excess connections need to be removed to establish normal function.

David Lewis, a neuroscientist at the University of Pittsburgh, studies the development of the prefrontal cortex in monkeys, a brain area that undergoes considerable reorganization at puberty. The prefrontal cortex contains discrete striplike clusters of axon terminals. During puberty, the stripes shrink dramatically in size, and some disappear entirely. Lewis believes that these changes occur because axon terminals containing excitatory synapses are eliminated during puberty. This change, Lewis hypothesizes, produces modifications in how the prefrontal cortex processes information. Fewer and smaller stripes after puberty may give the adult animal a more focused, restricted, and sustained neuronal response to the stimulus that the animal must remember during the delay period. Our improved performance on delayed-response tasks that occurs throughout puberty might depend on eliminating axons and their associated excitatory synapses, rather than preserving more of them. Pruning is normal. Less is more.

Reflecting on his studies, Lewis thought that the synaptic preservation argument presented an interesting interpretation of the little we do know about the pruning that occurs at puberty. He would argue, however, that pruning or eliminating synapses is critical to achieving mature levels of cognitive ability. As he points out, working memory capacity in monkeys progressively improves as pruning in the prefrontal cortex proceeds, and it reaches mature levels only when pruning ends.

Despite its initial, intuitive plausibility, this synaptic preservation strategy does not make much neuroscientific sense. Any plausibility the strategy has derives from our desire to understand the mind and intelligence in terms of synaptic numbers and densities. A neural accounting approach gives us a concrete, quantitative measure for something that we otherwise find abstract and mysterious. Once we buy into the quantitative neural accounting image, it is natural to think that more is always better. Unfortunately, the brain -- at any age -- is more complicated than that.

THE FIRST STRAND UNRAVELED

Neuroscientists have made astounding progress over the past hundred years in their quest to understand how, as Kandel and Schwartz said, behavior depends on the formation of appropriate interconnections among neurons in the brain. They also realize that, despite a century of research, they remain closer to the beginning than to the end of this quest. Making the connection between behavior and synapses remains more of a neuroscientific Holy Grail than a set of commandments engraved on stone tablets. Neuroscientists engaged in this work are more like Lancelot than like Moses. This is not to demean the neuroscientific enterprise, but rather to emphasize the difficulty of the task.

Neuroscientists who study how the brain's fine structures -- neural circuits and synapses -- govern human behavior and cognitive capacity take justifiable pride in their progress and are rightly optimistic about the future of their science. Yet they are appropriately cautious in interpreting their work, emphasizing that much remains to be done before we can use the research to support specific policy-relevant claims about parenting, child care, and education. As Huttenlocher acknowledges, The persistence of exuberant synaptic connections during early childhood raises the question whether these connections may be of functional importance for the emergence of cognitive functions in the young child, and for compensation of the child's

brain focal injuries. Answers to these questions are not available at the present time. And as Pasko Rakic states, The connections between neuroanatomy, neurochemistry, and neurodevelopment on the one hand and behavioral research in cognition on the other are rather tenuous.42

The hundreds of thousands of measurements that neuroscientists have made that document a pattern of change in synaptic density in our brains over our lifetimes allow them to generate and support general hypotheses about how synapses support behavior. However, there is still much work to be done before we can move from general hypotheses to formulating and establishing specific relationships between particular changes in the brain and the appearance, acquisition, or learning of specific skills and behaviors. We have every reason to believe that behavior and intellect to ultimately depend, somehow, on how brain cells are connected. We are far from knowing exactly how the capacity for specific behaviors -- such as negotiating a busy street, recognizing a familiar face, understanding a voice-mail message, reading TV Guide -- or even the development of representational memory depends on specific neural connections.

Goldman-Rakic cautions that every time policy makers, educators, child-care providers, and parents look to brain science for answers to pressing questions, there is a danger and tendency to take what little is known about neural development, accept it uncritically, and interpret it as the neural basis of behavior.43 This is what has happened with the little that we know about early synapse formation and modification. This time around, uncritical acceptance and misinterpretation of what neuroscientists do know about these processes -- taking them as the neural basis of behavior -- have given us the first strand in the Myth of the First Three Years.

The neuroscience and its interpretations that I have reviewed here are the basis for a cautionary statement by Carla Shatz: Much research remains to be done before anyone can conclusively determine the types of sensory input that encourage the formation of particular neural connections in newborns.44

Parents and caretakers should take some solace from this. Brainpower does not depend on the number of synapses formed before age 3. Environmental input, including stimulation provided by parents, neither initiates early synapse formation nor influences when or at what level synaptic densities peak. If the development of representational memory is a suitable example, the brain develops, synaptic densities peak, and elementary behaviors first appear. Rather than this marking the end of the time we have to build better brains, it seems more likely to mark only the beginning of a long developmental and maturational period during which environmental stimulation and experience do matter.


43 Goldman-Rakic, Setting the Stage.

Capture Their Attention With a Radish and 9 Other Brain-Based Learning Strategies

By: Judy Willis, M.D., M.Ed.

For photo: Before information can enter the brain to become learning an involuntary filter select which sensory input gets the attention. Neuroimaging helps point the way to igniting students’ attentive interest.

Before students can make memories or learn, you must capture their attention. Based on my background as a neurologist and my experience as a classroom teacher, I’ve created this list of tips for any teacher to integrate brain-based, neuro-logical learning strategies to grab and hold students’ attention.

All learning enters the brain through the senses. The subconscious mind needs to be on automatic pilot to process the enormous amount information from the world available through all the senses. Neuroimaging studies provide support for classroom strategies that operate on the brain’s first sensory filter, a thin strip of brain tissue low down, just above the spinal column that determines what captivates attention. This primitive intake filter, called the reticular activating system (RAS), admits less than one percent of the sensory information available to it every second.

Much like other mammals, the human RAS favors intake of sights, sounds, smells, and tactile sensations that are most critical to survival. The RAS is a virtual editor that grants attention and admission to things that have changed in the environment with priority to changes that signal threat. When threat is perceived, the RAS automatically selects related sensory input and directs it to the lower, reactive brain where the involuntary
response is fight, flight, or freeze. If the change is assessed as not threatening, the RAS focuses on sights, sounds, movements, smells, and other changes that provoke curiosity or are recognized as potential sources of pleasure.

1. **Calm the nervous fox**: Think of students’ RAS as that of a fox, coming out of its den, alerting to changes such as new sounds. The howling of a predatory wolf would get first priority, but when that sound is gone, the new sounds and movements of a rabbit in the bush alerts focus as a potential yummy dinner. Keep your little foxes feeling unthreatened by consistent enforcement of class rules, where students feel safe, where they can count on adults to consistently enforce the rules that protect their bodies, property, and feelings from classmates or others who threaten them.

2. **Positive Anticipation**: Start the or class telling your students it will be a great day, you’re glad to see them, and they are in for a wonderful experience.

3. **Advertise**: Advertising upcoming unit with curiosity provoking posters or adding clues or puzzle pieces each day, invests students in predicting what lesson might be coming and gets the RAS primed to “select” the sensory input of that lesson when it is revealed. If a Star Wars movie is popular put up a sign, “TWENTY FOUR HOURS UNTIL THE FORCE ARRIVES.” The next day when you discuss forceful or powerful opening sentences for essays, centrifugal force, or forces of nature, you’ll have created anticipation, and that will harness attention.

4. **What you say (or don’t say)**: A sudden midsentence silence is a curiosity the RAS wants to investigate. A suspenseful pause in your speech before saying something important builds anticipation as the students alert to what you will say or do next.

5. **What’s New?** Change the seating arrangements, put up photos of last year’s students doing an activity your students will be doing, light a candle, put a new exciting poster relating to the new unit under the one that has been hanging and when you walk by, “inadvertently” bump into the wall so the old one falls down and the new one is suddenly revealed.

6. **Play a song** when students enter the room to promote curiosity, hence focus, when you tell students there will be a link between some words in the song and something in the lesson.

7. **Walk the walk**: If you behave in a novel manner, such as walking backwards, at the start of a lesson, the RAS will be primed by curiosity to follow along when you unroll a number line on the floor and begin a unit about negative numbers.

8. **That doesn’t make sense**: Cognitive dissonance or discrepant events promote attention when students see or hear something that is contrary to what they think they know or expect. You can promote RAS admission of lesson on estimating by overfilling a water glass until it spills. When students question or comment about what you did, respond, “I didn’t estimate how much it would hold.” What you say next will be granted passage through the filter.

9. **Rotate techniques**, lest the unexpected become expected. Greet students at the door with a riddle or a note card with a vocabulary word. The riddle answer or the definition of their word is posted at the table at which they should sit.
10. Radishes: There will be several minutes of curious excitement when your students enter the classroom and find a radish on each of their desks, but this time will be paid back – literally with interest. They will be engaged and motivated to discover the reason the radishes are there.

For young students, learning the names and characteristics of shapes, the radishes can become a lesson to develop the concept of roundness and evaluate what qualities make some radishes have greater “roundness” than others.

The lesson for older students might address a curriculum standard such as analysis of similarities and differences. The RAS will respond to the color, novelty, peer interaction of evaluating these objects, that are usually disdained when found in their salads, as they develop their skill of observation, comparison, contrast, and even prediction as to why the radishes that seemed so similar at first, become unique as they become detectives using magnifying glasses.

You can even spark interest in square roots when they guess the meaning of the radishes and someone predicts, “Radishes are root vegetables, I bet we’ll learn square roots!”

The multisensory, novel radish experience has a greater chance of becoming long-term memory as your students are likely to actually answer parents’ often ignored queries about, “What did you learn in school today?” Students will summarize the day’s learning as grateful parents give them the positive feedback of attentive listening. The impact of the radish as a novel object, and something they’d never expect to hear described by their child, now alerts their own RAS, and the stage is set for family discussion of the lesson beyond the doors of the classroom.

Once you have their attention, you empower your students to become engaged in their learning process. Using wonder (discrepant events), humor, movement, change, advertising, and provoking curiosity capture students’ attention. They will be ready to focus on the sensory input (information) in the lesson that relates to the radish, form connections and relationships, and achieve the ultimate goal of adding new knowledge into their memory storage centers.

A radish on students’ desks today will reward you when students are captivated and focus on the lesson attentively. The even greater rewards come months later when they remember the lesson on their year end tests, and years later when they use the memory of that lesson to find creative solutions to new problems and develop interests that sustain curiosity for life long learning.

And you’ll probably never see a radish again and think of it as just a root vegetable.
Toll the Death Knell for Bell Curves
BY JUDY WILLIS

Looking out at the attentive faces during math class, I recalled these same students several months before. They were looking out the window, playing with coins in their pockets, doodling in their notebooks or talking to tablemates about anything but mathematics.

About half of these middle school students started the school year in my class math phobic, frustrated or bored. The average scores and mastery on their first tests were about a C-plus. A graph of their grades at the time might have resembled a bell curve.

After I began offering opportunities to do detailed test correction papers and take retests to demonstrate what they learned, these students became interested in math, worked harder and grew in skill. By the spring term the lowest grade on any test was a B-plus, and standardized test scores matched the improved classroom grades. That was when an administrator imposed a harsh new rule on grading, and I had no choice but to leave that school.

Assessment is a necessary part of education, especially when formative feedback improves the quality of student performance and teacher instruction. However, bell-curved testing and course-grading systems tend to reduce motivation and increase student stress and alienation from school.

Students now more than ever need to feel some sense of control of their academic success, that they are more than numbers on a curve. Eliminating requisite bell-curve grading that opens up A and B grades to all students who achieve higher than 80 percent mastery of the material can to be a positive incentive for effort and achievement.

Building Confidence
Emotional well-being and self-confidence are valuable for cognition. Data from recent brain research using neuro-imaging studies indicate greater activity in the higher cognitive prefrontal regions during low-stress, high-engagement learning.
experiences and more brain activity in the automatic, reflex behavior networks when subjects are anxious. Support from cognitive evaluations associates better long-term memory of information learned during low-stress, high-engagement neurological states. The successful translation of sensory input to knowledge and long-term memory is contingent upon many factors and the stress response is one we can influence by reducing unnecessary classroom stress such as bell-curved grading.

Students build confidence when they achieve goals they value and their effort is recognized as they make progress toward these goals. Students do not have fully developed delayed-gratification skills during their school years. The neurological basis of this appears related to the fact that the last part of the brain to mature are the prefrontal lobe networks involved in executive function, reasoning, delayed gratification and goal setting. Students from kindergarten through high school need support and encouragement from their teachers to keep their efforts directed on long-term goal achievement.

Judging Students
Students are motivated when they value the goals they can achieve and consider them within their reach if they extend the effort that they understand will result in success. The bell curve does not allow for more than half of the students to receive grades indicative of success regardless of their knowledge and test scores. The bell-curve model of grading limits the number of students who can be recognized for above-average mastery because the more the class achieves, the higher the average mastery on graded tests becomes and the more the apex of the bell shifts to the right. Classwide achievement has a negative impact on tests scored on a bell curve. If the grade range is 80 to 100 percent, 100 becomes an A and 80 becomes a D. The bell-curve system fails to provide that encouragement or positive reinforcement for students’ steady efforts and mastery when all students achieve success.

A longitudinal study of middle schoolers noted that teachers who emphasize competitive comparisons of student ability discourage students from asking for help. With competitive grading, the bell curve compares students to each other, not to level of subject-matter comprehen-

sion. An analysis by Jonathan Fife, director emeritus of the ERIC Clearinghouse on Higher Education, described inaccuracies when bell-curve analysis is used to judge students. He reviewed experimental data where teachers were told they were being assigned high-achieving students but actually were given random cross-sections of students. The students in these classes scored highest in the grade level on the end-of-year standardized tests in Fife’s study.

He interpreted these and other results to support the theory that belief in students’ success can influence their learning. As such, learning-outcome differences can result from believing that all students have high potentials rather than expecting that only a few will be highly successful. The latter is the expectation dictated by the bell curve. Fife’s interpretation is that students can meet high expectations for performance when they have the opportunity to be exceptional and when effective educators provide the instruction.

Emphasis on traditional testing as the primary means of student comparisons on bar graphs and bell curves results in needless loss of confidence. When the goal is to discover what students have mastered in a course, the bell curve does not apply. Having a low end that is an equal match of the high end gives students the message that half of them will perform up to but not beyond a midpoint. Students respond to teacher expectations, so why restrict those expectations by imposing an artificial limit?

A Postscript
When my best efforts to explain the importance of positive, formative assessment — rather than the punitive feedback of bell-curve grading — failed to convince the administrator of the school where I had been teaching, I did not return to that school. When I interviewed for the teaching position I now enjoy at Santa Barbara Middle School my first question for the head of the school was this: “Do you require teachers to grade on a bell curve?”

WILLIS OVERTS

Headmaster Steve Lane responded: “Why would anyone still do THAT?”

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Research-Based Strategies to Ignite Student Learning,
Insights From a Neurologist and Classroom Teacher.
Changing Education, One Brain at a Time

"My first personal revelations about education came to me not as a classroom teacher, but as a neuroscience researcher," says Judy Willis, MD, MEd. "In 1970, as a pre-med college student, I was using one of the first-generation electron microscopes to examine synapses connecting brain cells in baby chicks. My heart still races as I recall the night. As I sat alone in the darkroom of the science center developing my electron micrographs, I noticed a greater collection of protein in the synapses of some chicks that had been trained to follow a moving light. It was visible proof of something that had been, until that moment, only an abstract concept: the idea that learning changes the brain's structure. Since then I have been vitally interested in both neurology and the neuroscience of learning."

Willis turns the old axiom “Those who can, do; those who can't, teach” on its head. After graduating Phi Beta Kappa as the first woman graduate from Williams College, Willis received her medical degree from UCLA School of Medicine where she completed her medical and neurology residencies, including chief residency. However, she left practice after 15 years to earn her Master’s degree in education and teaching credentials from the University of California, Santa Barbara. Her teaching experience has ranged from elementary and middle school to college and graduate schools. Currently, she is adjunct faculty at University of California, Santa Barbara, and dedicates most of her time to giving presentations and workshops to educators and parents nationally and internationally about how the brain learns and strategies she considers consistent with the research.

Through it all, her observations on how the brain learns have led Willis to advocate for greater awareness of this process by both teachers and their students. Willis seeks to incorporate teaching the neurology of learning as part of a teacher’s overall education. Her goal is to turn around the increasing dropout rate among students, retain quality teachers, and develop 21st Century skill sets for all students. To accomplish that, she wants to empower children and their parents, as well as teachers.

"Every child should know he or she can change their brains to reach the academic, social, and emotional intelligence to which they strive. To accomplish this, we need to incorporate the teaching of the neurology of learning (neuroplasticity, stress, attention, dopamine, etc.) into schools of teacher education."

Lack of engagement by a child in the classroom suggests to Willis that adjustments need to be made to help the child learn more effectively. "If the joy of learning is not evident, or if motivation and enthusiasm for learning is not the same as it was before your child entered school, or if teachers report behavior problems or not ‘working up to potential’; those are all possible indicators that a child is not in the best environment for reaching his or her highest potential."

To help remedy that, Willis has written several books and articles with content specifically geared to the needs of educators, parents, and even the students themselves. “I wrote my first book for parents, How Your Child Learns Best: Brain-Based Ways to Ignite Learning and Increase School Success, to offer them the techniques and activities I used with my students that correlate with the developments in the neuroscience of how the brain learns. In that book I focused on suggestions for improving children’s engagement with the joy of learning to empower them to connect with school with more motivation so they could increase attentive focus, memory, higher-level thinking, and reasoning.”

Her most recent book, Inspiring Middle School Minds: Gifted, Creative, and Challenging, was published last year, and now Willis is working on a new series of Brain Owner’s Manual books for parents. They will include age-appropriate language that parents can use to share the discoveries of brain research with their children and to inform them about their own brain.
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"I never knew how much 'the' AAN was available to be 'my' AAN until I participated in the Palatucci Forum."

—Judy Willis, MD, MEd

potential. "I provide parents with the background information and reasons why parents can and should become active in sharing the neurology of learning with their children. Through this journey together into the wonders of the brain, parents also can help connect classroom lessons with their child's individual needs, gifts, and challenges. Learning can become active and include creative exchanges of ideas. Parents can bring life back into their children's learning while helping them build the critical thinking, problem solving, and reasoning skills that are being sacrificed with a rote memorization approach to teaching."

The parent book series will be followed by a similar series for educators with specific classroom strategies for teaching students that genius is more than their genes and they can change their brains to change their intelligence. This series is based on the Brain Owner's Manual lessons she created and taught to her own students.

As reported in the March/April issue of Neurology Now, Willis has collaborated with actress Goldie Hawn on the MindUp! Program, supported by Hawn's foundation. The program incorporates Willis' research evaluations and provides educators with Brain Links that explain the brain benefits of 15 activities designed to make students more aware of the learning process and enhance their classroom experiences.

Willis is dismayed by the "teaching to the test" attributes of the No Child Left Behind education legislation, as it fosters rote memorization over true comprehension and deprives teachers of the chance to take more individualized and creative approaches to their topics. She knows that to change this, she needs to change some minds in Washington. Thus, Willis applied to attend the AAN's Donald M. Palatucci Advocacy Leadership Forum. Her participation in the January 2010 Forum was an eye-opening experience on several levels.

"I never knew how much 'the' AAN was available to be 'my' AAN until I participated in the Palatucci Forum. Not only was the fellowship training experience and preparation wonderfully planned and executed better than any professional development or institute I've attended previously, but the quality of the AAN professional staff continues to inspire me. Knowing that people I respect believe in the work I'm doing and are there to support me motivates me to persevere—which is exactly the classroom experience that empowers our children when we have great teachers."

More information on Willis's work and additional education resources can be found at www.RADTeach.com. Details on the AAN's award-winning Palatucci Advocacy Leadership Forum can be found at www.aan.com/pal; applications for the January 2011 advocacy training are due by September 19.

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It's Not Spam... It's AANe-news!
Neurodevelopmental changes in working memory and cognitive control
Silvia A Bunge1,2 and Samantha B Wright2

One of the most salient ways in which our behavior changes during childhood and adolescence is that we get better at working towards long-term goals, at ignoring irrelevant information that could distract us from our goals, and at controlling our impulses — in other words, we exhibit improvements in cognitive control. Several recent magnetic resonance imaging studies have examined the developmental changes in brain structure and function that underlie improvements in working memory and cognitive control. Increased recruitment of task-relevant regions in the prefrontal cortex, parietal cortex and striatum over the course of development is associated with better performance in a range of cognitive tasks. Further work is needed to assess the role of experience in shaping the neural circuitry that underlies cognitive control.

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Current Opinion in Neurobiology 2007, 17:243-250
This review comes from a themed issue on Cognitive neuroscience
Edited by Keiji Tanaka and Takeo Watanabe

Available online 23rd February 2007
0959-4388/$ - see front matter
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DOI 10.1016/j.conb.2007.02.005

Introduction
If you ask a young child to choose between having one cookie now and two cookies in fifteen minutes, it is likely that he or she will initially attempt self-restraint in favor of the larger snack, but ultimately request the single cookie before the time is up [1,2]. Indeed, one of the most obvious ways in which our behavior changes during childhood and adolescence is that we get better at working towards long-term goals, ignoring irrelevant information that could distract us from these goals, and controlling our impulses — in other words, our cognitive control improves [3,4].

What precisely is changing in a child's brain over time, enabling him or her to better control his or her thoughts and behavior? To what extent do these neural changes result from experience and practice, and to what extent do they result from predictable developmental changes in brain structure? What are the elemental control processes that develop during childhood?

Several brain imaging studies have been conducted in recent years in an effort to tackle these and other difficult questions about the developing brain [5-7]. Compared with what is known about changes in brain structure during development (Box 1), far less is known about the resulting changes in brain function. In this review, we focus on event-related functional magnetic resonance imaging (fMRI) studies from the past year that examine age-related changes in working memory and cognitive control.

Visuospatial working memory
Since the first fMRI study of working memory in children just over a decade ago [8], most such studies have focused on pure maintenance of memory, and specifically on visuospatial working memory (VSWM) [9-11,12]. Event-related fMRI studies have shown that regions that have been strongly implicated in VSWM in adults — the superior frontal sulcus (SFS) and the intraparietal sulcus (IPS) — are increasingly engaged as childhood progresses [10,11]. Moreover, increased fractional anisotropy in frontoparietal white matter is positively correlated with blood oxygen level dependent (BOLD) activation in the SFS and IPS, and with VSWM capacity [13]. These data indicate that increased interaction between the SFS and IPS over development is important for improvements in VSWM.

Although these regions are increasingly engaged over childhood and adolescence, others are less so. For instance, Scherf et al. [12] found that children weakly recruited core working-memory regions (the dorsolateral prefrontal cortex [DLPFC] and parietal regions) and instead relied primarily on ventromedial regions (the caudate nucleus and anterior insula). In adolescence, by contrast, they observed refinements of the specialized network found in adults [3,12,14]. These results suggest that the maturation of adult-level cognition involves first an integration of childhood compensatory network with that of the more mature performance-enhancing regions, and next an increase in localization within those necessary regions (Figure 1).

At the cellular level, three possible developmental changes could account for the developmental increases in SFS and IPS activation that are observed during fMRI: pruning of excess neurons, myelination and increased strength of connections within or between brain regions.
Box 1  Developmental changes in brain structure and function

By the time a child starts primary school, the shape and size of his or her brain is roughly comparable to that of an adult. However, structural differences are evident upon closer examination [45]. Cortical gray matter volume, which reflects neuronal density and the number of connections between neurons, peaks at around age 10-12 in both prefrontal and parietal cortices — regions that have been strongly implicated in working memory and cognitive control [46]. Thereafter, gray matter loss occurs at different rates in different subregions of the brain, and is considered an index of the time-course of maturation of a region [47]. The dynamics of gray matter increases and decreases, particularly in the prefrontal cortex (PFC), are associated with differences in intellectual ability [48]. Within the PFC, gray matter reduction is completed earliest in the orbitofrontal cortex, followed by the ventrolateral PFC (VLPFC) and then by the dorsolateral PFC (DLPFC) [49]. It has been argued that differences in maturation time-course between prefrontal subregions partially account for differences in the rate of development of distinct cognitive control processes [19,27,50].

Unlike gray matter, white matter volume increases with age, reflecting myelination and increased axon thickness [46]. Diffusion tensor imaging (DTI) studies have shown greater coherence of white matter tracts in adults than in children, as measured by an index of fractional anisotropy [51]. Importantly, greater coherence is associated with better performance on tasks that require interaction between regions that are connected by these tracts [13,52,53]. In summary, both cortical pruning within brain regions and increased neuronal connectivity within and between regions could underlie improvements in cognitive control over development [21].

In a cutting-edge study, Klingberg and colleagues [16**] took a computational approach to determine which of these changes could contribute to the developmental changes observed in their VSWM studies. They concluded that the greater prefrontal and parietal activation and interactions that are observed in adults relative to children could result from increased strength of connectivity between regions, but not from pruning, myelination or the strength of connectivity within regions (Figure 2).

Interference suppression during performance of a VSWM task

A further VSWM study by Olesen, Klingberg and colleagues [17] included a period of distraction, during which participants were asked to ignore stimuli appearing in various locations on a screen. Children around the age of 13 exhibited greater SFS activation than did adults during this period of distraction, despite having shown reduced activation in this region in VSWM studies that did not involve distraction. Given that SFS is involved in spatial working memory, this finding suggests that the children were less effective at engaging the irrelevant spatial stimuli.

By contrast, adults engaged the right DLPFC and bilateral intraparietal cortex more strongly than children did while maintaining relevant information online. This finding is potentially significant in light of a prior study in adults by Sakai, Rowe and Passingham [18]. Using a similar task with adults, Sakai et al. showed that engagement of a slightly anterior region of the right DLPFC was associated with better performance on the working-memory task. Thus, in the study by Olesen et al. [17], children showed weaker activation during VSWM in a region of the right DLPFC that adults might rely on to create a distractor-resistant memory trace. It would be of great interest to examine developmental changes in the functional interactions between the DLPFC, SFS and IPS, and how these changes affect the ability to suppress interference [18].

Non-spatial working memory

Although the majority of developmental fMRI studies of working memory have focused on VSWM, a recent study by Crone, Bunge and colleagues [19] focused on development of non-spatial working memory. Participants had to remember a series of three nameable objects; children made more errors than adolescents and adults, but engaged highly overlapping brain regions during task performance. Positive correlations between accuracy and activation across the entire group were observed in all regions of interest: the ventrolateral prefrontal cortex (VLPFC), the DLPFC and the superior parietal cortex. These correlations remained significant after controlling for age, suggesting that the level of engagement of these regions itself has an impact on performance. Taken together with the aforementioned VSWM studies, these findings indicate not only that the basic working-memory circuitry is in place by middle childhood (see also [20]), but also that working-memory circuitry is strengthened during middle childhood.

Manipulation of items in working memory

As we have already noted, improvements in the ability to maintain information on-line are observed during childhood, and — when highly sensitive measurements are used — throughout adolescence [7]. However, developmental changes are more dramatic when one must manipulate, or work with, information held in working memory [21].

The aforementioned working-memory study by Crone et al. [19] provided evidence for protracted neurodevelopmental changes in regions involved in manipulating items in working memory relative to regions involved in simply maintaining items in working memory. Prior imaging research in adults had implicated the DLPFC and superior parietal cortex in manipulation [22]. In the Crone et al. study [19], adolescents and adults, but not 8-12-year olds, engaged the right DLPFC and bilateral superior parietal cortex when it was necessary to reverse the order of items held in working memory (Figure 3). Unlike the older age groups, 8-12-year olds did not recruit additional regions for manipulation above and beyond
what they would use for pure maintenance; this reliance on maintenance circuitry was associated with suboptimal manipulation ability. Such lower engagement of the DLPFC in children than in adults has also been observed in other studies of working memory and cognitive control [15,17].

These data do not address the issue of whether children fail to recruit brain regions that are involved in manipulation because of maturational constraints associated with immature neural circuitry, and/or because of limited practice with this type of task. Interestingly, in the study by Crone et al. [19], the children did recruit these DLPFC and superior parietal regions during encoding and response selection — just not during the delay period, when manipulation was required. A pattern of mature DLPFC activation has also been observed in 8–12-year olds performing a simple gambling task, even though age-related differences associated with the processing of uncertainty and negative feedback were observed in anterior cingulate cortex and lateral orbitofrontal cortex, respectively [23].

These observations highlight a general point about developmental changes in brain function: a region can exhibit adult-like patterns of activation in one task but not in another. As another example, VLPFC showed a mature pattern of activation in the non-spatial working-memory task [19], but not in tasks that involved response inhibition [24–26] or rule representation [27]. Thus, a region might contribute effectively to a neural circuit that underlies one task or cognitive function, but not to a neural circuit that underlies another.

Response control: inhibition and selection

Improvements are observed over childhood in the ability to control our actions [4]. Control is needed when one must inhibit a tendency to respond to a stimulus (i.e. 'response...
Cellular mechanisms underlying increased engagement of working-memory circuitry over development. (a) Edin et al. [16*] sought to determine the underlying structural changes over development that could explain why BOLD activation in the superior frontal sulcus (SFS) and the intraparietal sulcus (IPS) during VSTM performance is greater for adults (shown in green) than for children (black). (b) They used a model of VSTM to determine which of the known neural changes across development — pruning, myelination and/or increased strength of connection between neurons within (w) or between (b) brain regions — could contribute to the developmental changes observed in BOLD activation during VSTM performance. Based on these known changes, Edin et al. put forth five hypotheses (H1–H5) regarding the structural development of the VSTM network, and simulated the consequences of each of these structural changes on BOLD activation levels. For each hypothesis, a ‘child’ (black) and ‘adult’ (green) version of the network was created. The strengths of connections within a region are indicated by the connection curves inside the circles (which represent the parietal and frontal pyramidal cell populations), whereas the curves between the circles show connection curves between regions. By comparing these simulated outcomes with their empirical data, Edin et al. concluded that their data could be explained by increased strength of connectivity between regions (H4) but not by increased strength of connectivity within a region (H3), synaptic pruning (H5 and H3) or myelination (H2). See [16*] for more details. Reproduced, with permission, from [16*] © MIT Press.

inhibition'); this ability is typically measured using Go-No-Go and stop-signal paradigms [24–26,28–30,31**]. Control of responses is also needed when one must select between competing response alternatives ('response selection'). Neurodevelopmental changes in response control have been studied using various paradigms, including the Simon task [32*], antisaccade task [9], Eriksen flanker task [24,30,32*] and Stroop task [33–35]. Although these tasks differ in many ways and are therefore likely to rely on distinct cognitive processes, many of them test common underlying neural substrates that support controlled responding.

As such, to understand better the development of brain networks that underlie response control, it is crucial to determine which age-related differences are task-specific
and which generalize across several paradigms [24,30,32*]. An earlier fMRI study [24] combining elements of the Go-No-Go and flanker tasks revealed that children aged 8–12 failed to engage a region in the right VLPFC that young adults recruited for both response selection and inhibition. It has since been shown that adults with damage to the right VLPFC have difficulty in several tasks that involve response control [36], and a developmental study by Rubia et al. [26] further shows a positive correlation between activation of the right VLPFC and age (between 10–42 years) during successful versus unsuccessful inhibitions on the stop-signal paradigm (Figure 4; for a similar correlation in a developmental Stroop study, see [35]). These findings indicate that suboptimal response control in children and adolescents stems from insufficient recruitment of the right VLPFC and functionally connected regions, including the thalamus, caudate and cerebellum [26].

Another recent study by Rubia et al. [32*] combined three tasks that involve response control: Go–No-Go, Simon and attentional set-shifting tasks. The investigators compared activation on all three tasks for youths aged 10–17 and adults aged 20–43. In all three tasks, adults recruited portions of the prefrontal cortex, anterior cingulate cortex and striatum more strongly than the youths, and there was a positive linear correlation with age in task-relevant frontal and striatal regions. Additionally, adults engaged the inferior parietal cortex more strongly than youths on the Simon and set-shifting tasks [32*], and a similar finding has previously been reported for the Go–No-Go task [24].

Crone et al. [19*] examined age-related differences in activation of the DLPFC during working-memory manipulation. (a) Each trial of the working-memory task started with 250 ms fixation of a cross, followed by three nameable objects that were presented for 750 ms each, with a 250 ms presentation of the fixation cross between each nameable object. Forward trials required pure maintenance, whereas backward trials required manipulation in addition to maintenance. After the last object, the instruction ‘forward’ or ‘backward’ was presented for 500 ms (a forward trial is shown here). Participants were instructed to mentally rehearse or reorder the names of the three objects during the 6000 ms delay, and then to indicate using a button press whether the probe object was the first, second or third object in the forward or backward sequence. (b) Activation of regions of interest in the right DLPFC (Brodmann area 9) was functionally defined during the 6000 ms memory delay period; signal intensity was identified from a contrast of all conditions relative to fixation for all participants. Unlike adolescents and adults, children aged 8–12 failed to recruit the DLPFC more strongly in manipulation trials than in maintenance trials during the delay period. Group-averaged time courses of activation in the VLPFC and DLPFC on forward and backward trials are presented for each age group. The group-averaged time courses illustrate the finding that adults and adolescents, but not children aged 8–12, showed clear sustained DLPFC activity during the delay period. Reproduced, with permission, from pp. 9316–9317 of [19*]. © National Academy of Sciences.
Rubia et al. [31**] examined developmental changes in activation during response inhibition on a stop-signal paradigm. (a) Horizontal arrows were presented one at a time on the screen, and the participant pressed one of two buttons to indicate which direction the arrow was facing. However, 20% of the time, the horizontal arrow was followed by a vertical arrow, which signaled that the participant should inhibit their response. The interval of time between the presentation of the horizontal and vertical arrows was adjusted so the participant successfully inhibited their responses ~50% of the time. (b) Brain regions of increased activation in adults compared with children and adolescents (P < 0.01) during successful stop trials contrasted with unsuccessful stop trials. Depicted here in three-dimensional and horizontal sections is increased activation in right prefrontal cortex (Brodmann areas 44, 45 and 47), a region for which a greater difference between successful trials as compared with unsuccessful trials is observed in adults. From left to right, the slices correspond to z-coordinates of +4, 10, 14, 20 and 24. Reproduced, with permission, from [31**].

However, the lateralization and precise location of these age-related changes depended on the task at hand, further highlighting the need to seek converging evidence from multiple tasks.

Conclusions
In summary, a growing literature indicates that increased recruitment of task-related areas in frontal, parietal and striatal regions underlies improvements in working memory and cognitive control over the course of middle childhood and adolescence. The pattern of developmental changes in brain activation has been generally characterized as a shift from diffuse to focal activation [14**] and from posterior to anterior activation [32*,37]. Differences can be quantitative, with one age group engaging a region more strongly or extensively than another, and/or qualitative, with a shift in reliance on one set of brain regions to another [12*,32*,37,38]. Importantly, the precise pattern of change observed depends on the task, the ages being examined and the brain region in question.

By middle childhood, the ability to hold goal-relevant information in mind and use it to select appropriate actions is already adequate. It is of great interest to track brain function associated with working memory and cognitive control earlier in childhood, when these abilities are first acquired. Optical imaging studies can be conducted from infancy onwards [20,39], although the spatiotemporal resolution of this method is suboptimal (but see [40]). It is now possible to acquire fMRI data in children as young as four years of age [41*], although this is not without challenges such as head motion, low accuracy and poor attention span.

An important future direction is to determine the extent to which observed age differences in brain activation reflect hard developmental constraints (e.g. the required anatomical network is simply not in place at a given age) as opposed to lack of experience with a given type of task or cognitive strategy. Training studies involving several age groups would enable us to investigate effects of age and effects of practice independently, and to test whether age differences in performance and brain activation are still present after substantial practice [42–44]. So far, all but one [14**] of the published developmental fMRI studies on working memory or cognitive control have compared groups of individuals at different ages. These cross-sectional studies are valuable, but it is also important to conduct longitudinal studies to characterize intra-individual changes in brain function with age.

Acknowledgements
Featured research from the Bunge laboratory was funded by the National Science Foundation (NSF 0044884). We thank Karya Rubia and Bradley Schlaggar for helpful comments on a prior version of the manuscript.

References and recommended reading
Papers of particular interest, published within the period of review, have been highlighted as:
• of special interest
•• of outstanding interest

6. Casey BJ, Tottenham N, Liston G, Durston S: Imaging the developing brain: what have we learned about


13. This fMRI study used an oculomotor delayed-response task to study the development of visuospatial working memory. The authors observed qualitative shifts in which regions were recruited for task performance between childhood and adolescence. Further refinements took place between adolescence and adulthood.


16. This was the first combined cross-sectional and longitudinal fMRI study on the development of cognitive control. The authors explicitly compared between-group measurements of brain activation with within-person changes in brain function during performance of a Go-No-Go task. The two types of analysis yielded somewhat different results in the lateral prefrontal cortex, underscoring the need for further longitudinal brain imaging studies.


This study used computation methods to identify possible cellular maturational processes that support the development of visuospatial working memory. Strengthened connectivity between prefrontal and parietal regions was found to be the most likely candidate for the observed age-related increase in activation in these regions.


In this working-memory study, participants were asked to ignore distractor stimuli that appeared in various locations on the screen. Children exhibited greater SPS activation than adults during this period of distraction, suggesting that the children were less effective at ignoring the irrelevant stimuli.


fMRI data were acquired while children, adolescents and adults performed a task that required ordering items in working memory. The children's worse performance on the manipulation task was attributed to the lack of DLPCF and superior parietal engagement during manipulation.


This developmental fMRI study provided evidence that task-switching consists of separable processes that have distinct developmental time-courses: task-set suppression, which involves the medial prefrontal cortex and the basal ganglia; and rule representation, which involves VLPFC and reaches adults levels later than task-set suppression.


This fMRI study investigating children, adolescents and adults revealed a developmental trend of increased activation with age in the right inferior prefrontal cortex during successful inhibition, and also increased activation in the anterior cingulate cortex during failure of inhibition.


Developmental changes in brain activation were measured for three cognitive control tasks: a Simon task, an Eriksen flanker task, and a set-shifting task. For all three tasks, progressive maturation was found in task-specific frontal, striatal and parietal regions.


This activation was observed in four-year-olds and adults during numerical processing.

The change of prefrontal and parietal activation was observed in four-year-olds and adults during numerical processing.

The development of cognitive control was studied by using DTI while subjects performed a Go–No–Go task. Maturation of frontostriatal tracts was paralleled by an increase in efficiency and accuracy of response inhibition.
History teacher Rachel Otty often assigns group work in her classroom to keep her teens engaged.

In a warm, stuffy room on the third floor of Cambridge (Mass.) Rindge & Latin High School, 22 tenth graders in U.S. History I start their day by jotting down their opinions on how much progress has been made toward gender equity in the U.S. since women agitated for and won the right to vote.

Taking direction from a slide projected onto the blackboard, they break up into assigned groups of three to read charges against men leveled by 19th-century feminists in the 1848 Declaration of Sentiments, and compare them with statistics on the status of men and women in the U.S. today. They cut up pieces of paper labeled "government," "education," and "employment" and debate where to paste them on a line extending from "fully redressed" to "not redressed" based on current statistics.

After students return to their seats, their teacher, Rachel Otty, announces that next week the class will be divided into groups to prepare for a debate on whether or not President Andrew Jackson should have been impeached.

"I love debates!" a student blurts out.

Not so surprisingly, so does her teacher. "I remember history in high school as just lecturing, and I didn't enjoy it much," recalls Otty, who has garnered a reputation at the school for her skillful use of group work. "In graduate school, we learned about differentiated instruction, and group work is a way to do that. It's tough work and it requires a lot of brain power."

* * * *

Research by educators, psychologists, and, increasingly, neuroscientists supports Otty's personal experience. Done right, group work can harness the natural propensity of humans to interact, and—most important—make learning for a wide variety of students more engaging, memorable, and equitable. While it is more difficult to do than traditional lecturing, teachers say, most of the hard work is in the preparation, and the payoffs make the time invested well worth it.

Recent research by neuroscientists points to the existence of a "social brain" that enables humans to interact with each other. Summarizing the evidence gathered so far, Chris Frith, professor in neuropsychology at the Wellcome Trust Centre for Neuroimaging at University College London, has identified four regions of the brain associated with functions that allow humans to "read" others' states of mind and predict what they will do (see sidebar "The Brain
and Collaboration"). The Brain and Collaboration

According to British neuropsychologist Chris Frith, four regions of the brain are implicated in the human ability to interact with others. Among other things, these regions allow humans to read facial expressions (amygdala), to draw on knowledge from prior interpersonal experience (temporal poles), assess movement (posterior superior temporal sulcus/temporo-parietal junction), and think about others' mental states (medial prefrontal cortex). The ability to assign mental states to oneself and others—often referred to as “theory of mind”—has been documented in children as young as four, with precursor skills observed in infants less than one year old.

Brain-imaging studies also provide emerging evidence of a neurological "mirror system": When we observe a movement or emotion in someone else, the corresponding areas in our own brain are stimulated. It is as if we were actually experiencing the same movement or emotion ourselves.

The ability to interact and collaborate with others has been credited for humans' ability to rise to the top of the food chain despite being weaker than other species. In his popular book Brain Rules, John Medina, a developmental molecular biologist and director of the Brain Center for Applied Learning Research at Seattle Pacific University, illustrates this with the example of engaging an ally to help fight off a woolly mammoth by driving it off a cliff. "And there is ample evidence that this is exactly what we did," he writes. "[Humans] learned to cooperate, which means creating a shared goal that takes into account your allies' interests as well as your own."

At a seminar held in February at London's Royal Society for the Encouragement of Arts, Manufactures and Commerce (RSA) to discuss implications of the social brain for curriculum, Frith said there was "consensus that work on the social brain does argue for expanding the group learning and cooperative learning projects" in schools. "I certainly believe that the special feature of humans is that we can work together to achieve more than the sum of the individuals in the group. This is because we can share experiences," he wrote in an e-mail, adding, "But we do have to learn how best to do this."

Classroom Benefits of Group Work

In the classroom setting, researchers and teachers say the power of collaborating—typically in small groups—comes from three main activities: identifying and working out differing viewpoints, synthesizing and vocalizing one's own knowledge, and extending one's knowledge through hearing the ideas of others.

In a 1991 review of findings from studies comparing the academic outcomes of elementary and secondary students engaged in cooperative learning with those of control groups receiving traditional instruction, Robert E. Slavin, director of the Center for Research and Reform at the Johns Hopkins University School of Education, concluded that 37 of the 44 studies favored group learning over traditional learning as long as the cooperative learning approach included both a group task and individual accountability (see sidebar "Structuring Effective Group Work").

Structuring Effective Group Work

How much students get out of group work depends on how well it is structured and how thoroughly students are prepared in advance, researchers say.

In a comprehensive review of classroom studies comparing different types of group work, the late Stanford University education professor Elizabeth Cohen noted that productive group learning does not come naturally for students and that teachers can unwittingly assign group tasks that don't fit the definition of a "true group task."

True group work generally features an "ill-structured task" that has no right answer, often requires higher-level thinking, and can be accomplished only through interaction in a group, according to Cohen. Examples might include explaining how a balance scale works or coming up with an equation that can be used to buy different lengths of shoelaces for different types of shoes.

For productive cooperative learning to occur, students first need instruction on building cooperative skills including how to explain and receive feedback, stay on task, and encourage the contributions and monitor the understanding of others, she wrote.
In her classic work, *Designing Groupwork*, Cohen advised teachers to begin the year establishing “norms” for equal participation that stress listening, asking questions, and allowing everyone in the group to talk. Instruction by the teacher also should not be so specific that it limits the group conversation. Classrooms with the biggest learning gains were those where teachers “were able to delegate authority so that more children could talk and work together at multiple learning centers,” she wrote.

Teachers especially need to be attentive to the social and academic status of students in the classroom, which can affect the ability of both “high-” and “low-” status students to learn in groups, according to Helen Featherstone, a retired Michigan State University professor who is writing a book on group instruction based on Cohen’s work. High-status students may ignore or reject ideas from low-status students (even though they may be better or more accurate). Low-status students may assume “smart” kids are right and opt out of group discussions. Students who aren’t participating in the group may be doing so because they are being marginalized by peers, not because they are necessarily shy or “lazy.”

“When the group’s task is to ensure that every group member learns something, it is in the interests of every group member to spend time explaining concepts to his or her group mates,” Slavin wrote, while noting that students who learned the most “are those who give and receive elaborate explanations.”

Students who use the opportunity of working in a group to explain, clarify, and reiterate their understandings are facilitating what neuroscientists call “consolidation”—the process by which short-term “working memory” is converted to more permanent memory. This “mental manipulation” is different from “cramming,” which is not considered as effective and can even be counterproductive if done in a context of boredom, fear, or anxiety.

In addition to helping students retain knowledge, collaboration has also been shown to positively affect social climate in schools, student self-esteem, intergroup relations, acceptance of disabled students, and attitudes toward school, Slavin reported. He found academic benefits across the spectrum of grade levels (2–12), subjects, school type, and type of learner. Some researchers have noted particular benefits of group work for English Language Learners.

**Maximizing Participation: “Only the Person Who Thinks, Learns”**

Group work can also work against factors known to inhibit learning, such as the fear of making mistakes or becoming discouraged, says Judy Willis, a neurologist who has taught elementary and middle school in Santa Barbara for 10 years and often writes and speaks about how findings about the brain can inform teaching.

In her classes, she allot 50 percent of classroom time to group work. “Only the person who thinks, learns,” she says, “and you have to make mistakes to learn.” With the right pre-teaching and structure, small-group learning can decrease the fear of making mistakes in front of the whole class, thus increasing participation, she says. And participation is not only key to memory making, but also for tapping into the brain’s hormone-driven reward systems that reinforce successful interactions, keeping students involved in learning and persevering through challenging material, she says.

Group work can also increase engagement because individuals can be assigned roles that allow them to be “experts in something,” so that they can be challenged at a level appropriate to their understanding, she says. To discuss and present various theories for why the Jamestown settlement failed or why the dinosaurs became extinct, for example, more advanced students may be “producers” charged with stopping their group periodically to summarize what is being said; those with attention deficits might be assigned to be “prop directors” to keep track of supplies needed to make a chart for the final presentation. Over the course of the year, Willis works with students to build their skills in areas of weaknesses.

To identify students’ strengths and weaknesses, Willis begins each academic year with team-building exercises in which students pick a group name or cheer and then do a vocabulary or geography puzzle together, for example, before rotating to do the same in a different group. “By that time, I’ll know who they are academically,” Willis says.

The next activity will assess students’ social skill levels by teaching each group a game and then regrouping students
to teach their games to others. “Teaching the rules of a game is a pretty high-level function,” Willis explains. “You have to understand the rules, synthesize them and put them in language that someone else can understand. You also have to be patient, watch, and supervise—it’s a test of one’s executive function and maturity to teach a game you want to play before you can play it.”

**Planning, Pre-Teaching, and Powerful Results**

Once she is ready to incorporate a group project into the curriculum, Willis plans backward by asking herself, “What do I want them to know?” Then, she says, “I plan it so that they achieve that academic goal through what they do in the group.”

Pre-teaching skills are also key: Students can’t join groups until they answer questions from their notes or reading. “It’s not a free-for-all; it’s very structured,” she says.

Willis uses a rubric to keep track of both group and individual progress. She asks students in each group to use different-colored pencils so she can gauge participation levels as well. “There needs to be accountability; [otherwise] some will goof off; some will feel they have to do all the work—plenty of things can go wrong.”

But when things go right, says Willis, students are neither bored, oppositional, or turned off by school. She links this to the way that group work prepares the brain to handle new information.

“When information comes into the senses, once it gets to the amygdala [the part of the brain involved in emotions and memory], depending on the emotional state of the [student], the input is either going to be sent to the higher frontal cortex, which governs long-term memories, goal setting, and creative decision making, or the reactive brain, which we don’t control. In a group that allows people to enter with their strengths and interests, it’s set up for information being processed so they can remember it, use it, and conceptualize it,” says Willis.

While the planning and “front-loading” of lessons prior to group exercises is hard, “the student behavior and the quality and quantity of what they remember is the payoff,” says Willis. And while introducing group work can take a “leap of faith” for teachers faced with state mandates and inflexible curriculum in some school districts, she says, she has seen “excellent results” on standardized tests. As importantly, she says, “Parents say to me, ‘What are you doing? My child comes home and talks about what they are doing in school.’”

At the high school level, powerful results from a group approach to teaching math have also been documented by former Stanford professor Jo Boaler. In a five-year longitudinal study of 700 students published in 2008, Boaler followed the attitudes and outcomes of students who were taught math through the traditional “demonstrate and practice” approach at two suburban schools with those of a diverse urban school (called “Railside”), where teachers had created a sequence of theme-based math courses featuring group work. Although Railside students scored lower on a middle school math test than students at the other two schools, they outperformed the other students by their second year of high school and enrolled in advanced math courses at a higher rate by their senior year. The achievement gaps between white, black, and Latino students closed at Riverside, but not at the other schools.

* * * *

Back in Cambridge, Rachel Otty says she uses group work to help students understand difficult concepts or expose them to different viewpoints on an issue. She draws many activities from the History Alive! curriculum, which helps teachers find group exercises aligned with state standards. She also supplements the exercises with additional reading material from primary and secondary sources to provide additional content and context.

When creating groups, Otty typically chooses students of mixed ability for groups of four or fewer. She makes sure that students have at least one other person in the group with whom they can work cooperatively. She also mixes shy students with outgoing ones, as well as grouping those who are particularly distractible with those who are focused. Often she starts with the more distractible students and builds the groups around them. She typically gives students a rubric that explains how their individual effort will be graded and how their group presentation will be graded.
Since her high school adopted 82-minute blocks, Otty says, group work also serves as a good classroom management tool: She likes to break up the long blocks with three or four transitions during class to keep her teens busy. "That's what my student interns tell me, "Your students are always working,"" she says.

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