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In Search of . . . Brain-Based Education

By John T. Bruer

The "In Search of . . ." television series is no way to present history, Mr. Bruer points out, and the brain-based education literature is not the way to present the science of learning.

We have almost survived the Decade of the Brain. During the 1990s, government agencies, foundations, and advocacy groups engaged in a highly successful effort to raise public awareness about advances in brain research. Brain science became material for cover stories in our national newsmagazines. Increased public awareness raised educators' always simmering interest in the brain to the boiling point. Over the past five years, there have been numerous books, conferences, and entire issues of education journals devoted to what has come to be called "brain-based education."

Brain-based educators tend to support progressive education reforms. They decry the "factory model of education," in which experts create knowledge, teachers disseminate it, and students are graded on how much of it they can absorb and retain. Like many other educators, brain-based educators favor a constructivist, active learning model. Students should be actively engaged in learning and in guiding their own instruction. Brain enthusiasts see neuroscience as perhaps the best weapon with which to destroy our outdated factory model.[1] They argue that teachers should teach for meaning and understanding. To do so, they claim, teachers should create learning environments that are low in threat and high in challenge, and students should be actively engaged and immersed in complex experiences. No reasonable parent or informed educator would take issue with these ideas. Indeed, if more schools taught for understanding and if more teachers had the resources to do so, our schools would be better learning environments.

However, there is nothing new in this critique of traditional education. It is based on a cognitive and constructivist model of learning that is firmly rooted in more than 30 years of psychological research. Whatever scientific evidence we have for or against the efficacy of such educational approaches can be found in any current textbook on educational psychology.[2] None of the evidence comes from brain research. It comes from cognitive and developmental psychology; from the behavioral, not the biological, sciences; from our scientific understanding of the mind, not from our scientific understanding of the brain.

To the extent that brain-based educators' recipe for school and classroom change is well grounded in this behavioral research, their message is valuable. Teachers should know about short- and long-term memory; about primacy/recency effects; about how procedural, declarative, and episodic memory differ; and about how prior knowledge affects our current ability to learn. But to claim that these are "brain-based" findings is misleading.

While we know a considerable amount from psychological research that is pertinent to teaching and learning, we know much less about how the brain functions and learns.[3] For nearly a century, the science of the mind (psychology) developed independently from the science of the brain (neuroscience). Psychologists were interested in our mental functions and capacities -- how we learn, remember, and think. Neuroscientists were interested in how the brain develops and functions. It was as if psychologists were interested only in our mental software and neuroscientists only in our neural hardware. Deeply held theoretical assumptions in both fields supported a view that mind and brain could, and indeed should, be studied independently.

It is only in the past 15 years or so that these theoretical barriers have fallen. Now scientists called cognitive neuroscientists are beginning to study how our neural hardware might run our mental software, how brain structures support mental functions, how our neural circuits enable us to think and learn. This is an exciting and new scientific endeavor, but it is also a very young one. As a result we know relatively little about learning, thinking, and remembering at the level of brain areas, neural circuits, or synapses; we know very little about how the brain thinks, remembers, and learns.

Yet brain science has always had a seductive appeal for educators.[4] Brain science appears to give hard biological data and explanations that, for some reason, we find more compelling than the "soft" data that come from psychological science. But seductive appeal and a very limited brain science database are a dangerous combination. They make it relatively easy to formulate bold statements about brain science and education that are speculative at best and often far removed from neuroscientific fact. Nonetheless, the allure of brain science ensures that these ideas will often find a substantial and accepting audience. As Joseph LeDoux, a leading authority on the neuroscience of emotion, cautioned educators at a 1996 brain and education conference, "These ideas are easy to sell to the public, but it is easy to take them beyond their actual basis in science."[5]

And the ideas are far-ranging indeed. Within the literature on the brain and education one finds, for example, that brain science supports Bloom's Taxonomy, Madeline Hunter's effective teaching, whole-language instruction, Vygotsky's theory of social learning, thematic instruction, portfolio assessment, and cooperative learning.

The difficulty is that the brain-based education literature is very much like a docudrama or an episode of "In Search of . . ." in which an interesting segment on Egyptology suddenly takes a bizarre turn that links Tutankhamen with the alien landing in Roswell, New Mexico. Just where did the episode turn from archaeological fact to speculation or fantasy? That is the same question one must constantly ask when reading about brain-based education.

Educators, like all professionals, should be interested in knowing how basic research, including brain science, might contribute to improved professional practice. The danger with much of the brain-based education literature, as with an "In Search of . . ." episode, is that it becomes exceedingly difficult to separate the science from the speculation, to sort what we know from what we would like to be the case. If our interest is enhancing teaching and learning by applying science to education, this is not the way to do it. Would we want our children to learn about the Exodus by watching "In Search of Ramses' Martian Wife"?

We might think of each of the numerous claims that brain-based educators make as similar to an "In Search of . . ." episode. For each one, we should ask, Where does the science end and the speculation begin? I cannot do that here. So instead I'll concentrate on two ideas that appear prominently in brain-based education articles: the educational significance of brain laterality (right brain versus left brain) and the claim that neuroscience has established that there is a sensitive period for learning.

Left Brain, Right Brain: One More Time

"Right brain versus left brain" is one of those popular ideas that will not die. Speculations about the educational significance of brain laterality have been circulating in the education literature for 30 years. Although repeatedly criticized and dismissed by psychologists and brain scientists, the speculation continues.[6] David Sousa devotes a chapter of *How the Brain Learns* to explaining brain laterality and presents classroom strategies that teachers might use to ensure that both hemispheres are involved in learning.[7] Following the standard line, the *left hemisphere* is the logical hemisphere, involved in speech, reading, and writing. It is the analytical hemisphere that evaluates factual material in a rational way and that understands the literal interpretation of words. It is a serial processor that tracks time and sequences and that recognizes words, letters, and numbers. The *right hemisphere* is the intuitive, creative hemisphere. It gathers information more from images than from words. It is a parallel processor well suited for pattern recognition and spatial reasoning. It is the hemisphere that recognizes faces, places, and objects.

According to this traditional view of laterality, left-hemisphere-dominant individuals tend to be more verbal, more analytical, and better problem solvers. Females, we are told, are more likely than males to be left-hemisphere dominant. Right-hemisphere-dominant individuals, more typically males, paint and draw well, are good at math, and deal with the visual world more easily than with the verbal. Schools, Sousa points out, are overwhelmingly left-hemisphere places in which left-hemisphere-dominant individuals, mostly girls, feel more comfortable than right-hemisphere-dominant individuals, mostly boys. Hemispheric dominance also explains why girls are superior to boys in arithmetic -- it is linear and logical, and there is only one correct answer to each problem -- while girls suffer math anxiety when it comes to the right-hemisphere activities of algebra and geometry. These latter disciplines, unlike arithmetic, are holistic, relational, and spatial and also allow multiple solutions to problems.

Before we consider how, or whether, brain science supports this traditional view, educators should be wary of claims about the educational significance of gender differences in brain laterality. There are tasks that psychologists have used in their studies that reveal gender-based differences in performance. Often, however, these differences are specific to a task. Although males are superior to females at mentally rotating objects, this seems to be the only spatial task for which psychologists have found such a difference.[8] Moreover, when they do find gender differences, these differences tend to be very small. If they were measured on an I.Q.-like scale with a mean of 100 and a standard deviation of 15, these gender differences amount to around five points. Furthermore, the range of difference within genders is broad. Many males have better language skills than most females; many females have better spatial and mathematical skills than most males. The scientific consensus among psychologists and neuroscientists who conduct these studies is that whatever gender differences exist may have interesting consequences for the scientific study of the brain, but they have no practical or instructional consequences.[9]

Now let's consider the brain sciences and how or whether they offer support for some of the particular teaching strategies Sousa recommends. To involve the right hemisphere in learning, Sousa writes, teachers should encourage students to generate and use mental imagery: "For most people, the left hemisphere specializes in coding information verbally while the right hemisphere codes information visually. Although teachers spend much time talking (and sometimes have their students talk) about the learning objective, little time is given to developing visual cues." To ensure that the left hemisphere gets equal time, teachers should let students "read, write, and compute often."[10]

What brain scientists currently know about spatial reasoning and mental imagery provides counterexamples to such simplistic claims as these. Such claims arise out of a folk theory about brain laterality, not a neuroscientific one.

Here are two simple spatial tasks: 1) determine whether one object is above or below another, and 2) determine whether two objects are more or less than one foot apart. Based on our folk theory of the brain, as spatial tasks both of these should be right-hemisphere tasks. However, if we delve a little deeper, as psychologists and neuroscientists tend to do, we see that the information-processing or computational demands of the two tasks are different.[11] The first task requires that we place objects or parts of objects into broad categories -- up/down or left/right -- but we do not have to determine how far up or down (or left or right) one object is from the other. Psychologists call this *categorical* spatial reasoning. In contrast, the second task is a spatial *coordinate* task, in which we must compute and retain precise distance relations between the objects.

Research over the last decade has shown that categorical and coordinate spatial reasoning are performed by distinct subsystems in the brain.[12] A subsystem in the brain's *left* hemisphere performs categorical spatial reasoning. A subsystem in the brain's *right* hemisphere processes coordinate spatial relationships. Although the research does point to differences in the information-processing abilities and biases of the brain hemispheres, those differences are found at a finer level of analysis than "spatial reasoning." It makes no sense to claim that spatial reasoning is a right-hemisphere task.

Based on research like this, Christopher Chabris and Stephen Kosslyn, leading researchers in the field of spatial reasoning and visual imagery, claim that any model of brain lateralization that assigns conglomerations of complex mental abilities, such as spatial reasoning, to one hemisphere or the other, as our folk theory does, is simply too crude to be scientifically or practically useful. Our folk theory can neither explain what the brain is doing nor generate useful predictions about where novel tasks might be computed in the brain.[13] Unfortunately, it is just such a crude folk theory that brain-based educators rely on when framing their recommendations.

Visual imagery is another example. From the traditional, folk-theoretic perspective, generating and using visual imagery is a right-hemisphere function. Generating and using visual imagery is a complex operation that involves, even at a crude level of analysis, at least five distinct mental subcomponents: 1) to create a visual image of a dog, you must transfer long-term visual memories into a temporary visual memory store; 2) to determine if your imagined dog has a tail, you must zoom in and identify details of the image; 3) to put a blue collar on the dog requires that you add a new element to your previously generated image; 4) to make the dog look the other way demands that you rotate your image of the dog; and 5) to draw or describe the imagined dog, you must scan the visual image with your mind's eye.

There is an abundance of neuroscientific evidence that this complex task is not confined to the right hemisphere. There are patients with brain damage who can recognize visual objects and draw or describe visible objects normally, yet these patients cannot answer questions that require them to generate a mental image. ("Think of a dog. Does it have a long tail?") These patients have long-term visual memories, but they cannot use those memories to generate mental images. All these patients have damage to the rear portion of the left hemisphere.[14]

Studies on split-brain patients, people who have had their two hemispheres surgically disconnected to treat severe epilepsy, allow scientists to present visual stimuli to one hemisphere but not the other. Michael Gazzaniga and Kosslyn showed split-brain patients a lower-case letter and then asked the patients whether the corresponding capital letter had any curved lines.[15] The task required that the patients generate a mental image of the capital letter based on the lower-case letter they had seen. When the stimuli were presented to the patients' left hemispheres, they performed perfectly on the task. However, the patients made many mistakes when the letter stimuli were presented to the right hemisphere. Likewise, brain-imaging studies of normal adult subjects performing imagery tasks show that both hemispheres are active in these tasks.[16] Based on all these data, brain scientists have concluded that the ability to generate visual imagery depends on the left hemisphere.

One of the most accessible presentations of this research appears in *Images of Mind*, by Michael Posner and Mark Raichle, in which they conclude, "The common belief that creating mental imagery is a function of the right hemisphere is clearly false."[17] Again, different brain areas are specialized for different tasks, but that specialization occurs at a finer level of analysis than "using visual imagery." Using visual imagery may be a useful learning strategy, but if it is useful it is not because it involves an otherwise underutilized right hemisphere in learning.

The same problem also subverts claims that one hemisphere or the other is the site of number recognition or reading skills. Here is a simple number task, expressed in two apparently equivalent ways: What is bigger, two or five? What is bigger, 2 or 5? It involves recognizing number symbols and understanding what those symbols mean. According to our folk theory, this should be a left-hemisphere task. But once again our folk theory is too crude.

Numerical comparison involves at least two mental subskills: identifying the number names and then comparing the numerical magnitudes that they designate. Although we seldom think of it, we are "bilingual" when it comes to numbers. We have number words -- e.g., *one, two* -- to name numbers, and we also have special written symbols, Arabic numerals -- e.g., *1, 2*. Our numerical bilingualism means that the two comparison questions above place different computational demands on the mind/brain. Using brain-recording techniques, Stanislaus Dehaene found that we identify number words using a system in the brain's left hemisphere, but we identify Arabic numerals using brain areas in both the right and left hemispheres. Once we identify either the number words or the Arabic digits as symbols for numerical quantities, a distinct neural subsystem in the brain's right hemisphere compares magnitudes named by the two number symbols.18

Even for such a simple number task as comparison, both hemispheres are involved. Thus it makes no neuroscientific sense to claim that the left hemisphere recognizes numbers. Brain areas are specialized, but at a much finer level than "recognizing numbers." This simple task is already too complex for our folk theory to handle. Forget about algebra and geometry.

Similar research that analyzes speech and reading skills into their component processes also shows that reading is not simply a left-hemisphere task, as our folk theory suggests. Recognizing speech sounds, decoding written words, finding the meanings of words, constructing the gist of a written text, and making inferences as we read all rely on subsystems in both brain hemispheres.19

There is another different, but equally misleading, interpretation of brain laterality that occurs in the literature of brain-based education. In *Making Connections,* Renate Caine and Geoffrey Caine are critical of traditional "brain dichotomizers" and warn that the brain does not lend itself to such simple explanations. In their view, the results of research on split brains and hemispheric specialization are inconclusive -- "both hemispheres are involved in all activities" -- a conclusion that would seem to be consistent with what we have seen in our brief review of spatial reasoning, visual imagery, number skills, and reading.

However, following the folk theory, they do maintain that the left hemisphere processes parts and the right hemisphere processes wholes. In their interpretation, the educational significance of laterality research is that it shows that, within the brain, parts and wholes always interact. Laterality research thus provides scientific support for one of their principles of brain-based education: the brain processes parts and wholes simultaneously. Rather than number comparison or categorical spatial reasoning, the Caines provide a more global example: "Consider a poem, a play, a great novel, or a great work of philosophy. They all involve a sense of the 'wholeness' of things and a capacity to work with patterns, often in timeless ways. In other words, the 'left brain' processes are enriched and supported by 'right brain' processes."20

For educators, the Caines see the two-brain doctrine as a "valuable metaphor that helps educators acknowledge two separate but simultaneous tendencies in the brain for organizing information. One is to reduce information to parts; the other is to perceive and work with it as a whole or a series of wholes."21 Effective brain-based educational strategies overlook neither parts nor wholes, but constantly attempt to provide opportunities in which students can make connections and integrate parts and wholes. Thus the Caines number among their examples of brain-based approaches whole-language instruction,22 integrated curricula, thematic teaching, and cooperative learning.23 Similarly, because we make connections best when new information is embedded in meaningful life events and in socially interactive situations, Lev Vygotsky's theory of social learning should also be highly brain compatible.24

To the extent that one would want to view this as a metaphor, all I can say is that some of us find some metaphors more appealing than others. To the extent that this is supposed to be an attempt to ground educational principles in brain science, the aliens have just landed in Egypt.

Where did things go awry? Although they claim that laterality research in the sense of hemispheric localization is inconclusive, the Caines do maintain the piece of our folk theory that attributes "whole" processing to the right hemisphere and "part" processing to the left hemisphere. Because the two hemispheres are connected in normal healthy brains, they conclude that the brain processes parts and wholes simultaneously. It certainly does -- although it probably is not the case that wholes and parts can be so neatly dichotomized. For example, in visual word decoding, the right hemisphere seems to read words letter by letter -- by looking at the parts -- while the left hemisphere recognizes entire words -- the visual word forms.25

But again, the parts and wholes to which the brain is sensitive appear to occur at quite a fine-grained level of analysis -- categories versus coordinates, generating versus scanning visual images, identifying number words versus Arabic digits. The Caines' example of part/whole interactions -- the left-hemisphere comprehension of a text and the right-hemisphere appreciation of wholeness -- relates to such a highly complex task that involves so many parts and wholes at different levels of analysis that it is trivially true that the whole brain is involved. Thus their appeal to brain science suffers from the same problem Kosslyn identified in the attempts to use crude theories to understand the brain. The only brain categories that the Caines appeal to are parts and wholes. Then they attempt to understand learning and exceedingly complex tasks in terms of parts and wholes. This approach bothers neither to analyze the brain nor to analyze behaviors.

The danger here is that one might think that there are brain-based reasons to adopt whole-language instruction, integrated curricula, or Vygotskian social learning. There are none. Whether or not these educational practices should be adopted must be determined on the basis of the impact they have on student learning. The evidence we now have on whole-language instruction is at best inconclusive, and the efficacy of social learning theory remains an open question. Brain science contributes no evidence, pro or con, for the brain-based strategies that the Caines espouse.

The fundamental problem with the right-brain versus left-brain claims that one finds in the education literature is that they rely on our intuitions and folk theories about the brain, rather than on what brain science is actually able to tell us. Our folk theories are too crude and imprecise to have any scientific, predictive, or instructional value. What modern brain science is telling us -- and what brain-based educators fail to appreciate -- is that it makes no scientific sense to map gross, unanalyzed behaviors and skills -- reading, arithmetic, spatial reasoning -- onto one brain hemisphere or another.

Brains Like Sponges: The Sensitive Period

A new and popular, but problematic, idea found in the brain-based literature is that there is a critical or sensitive period in brain development, lasting until a child is around 10 years old, during which children learn faster, easier, and with more meaning than at any other time in their lives. David Sousa presented the claim this way in a recent commentary in *Education Week,* titled "Is the Fuss About Brain Research Justified?"

> As the child grows, the brain selectively strengthens and prunes connections based on experience. Although this process continues throughout our lives, it seems to be most pronounced between the ages of 2 and 11, as different development areas emerge and taper off. . . . These so-called "windows of opportunity" represent critical periods when the brain demands certain types of input to create or consolidate neural networks, especially for acquiring language, emotional control, and learning to play music. Certainly, one can learn new information and skills at any age. But what the child learns during that window period will strongly influence what is learned after the window closes.[26]

In a recent *Educational Leadership* article, Pat Wolfe and Ron Brandt prudently caution educators against any quick marriage between brain science and education. However, among the well-established neuroscientific findings about which educators can be confident, they include, "Some abilities are acquired more easily during certain sensitive periods, or 'windows of opportunity.'" Later they continue, "During these years, [the brain] also has a remarkable ability to adapt and reorganize. It appears to develop some capacities with more ease at this time than in the years after puberty. These stages once called 'critical periods' are more accurately described as 'sensitive periods' or 'windows of opportunity.'"[27] Eric Jensen, in *Teaching with the Brain in Mind,* also writes that "the brain learns fastest and easiest during the school years."[28]

If there were neuroscientific evidence for the existence of such a sensitive period, such evidence might appear to provide a biological argument for the importance of elementary teaching and a scientific rationale for redirecting resources, restructuring curricula, and reforming pedagogy to take advantage of the once-in-a-lifetime learning opportunity nature has given us. If teachers could understand when sensitive periods begin and end, the thinking goes, they could structure curricula to take advantage of these unique windows of opportunity. Sousa tells of an experienced fifth-grade teacher who was upset when a mother asked the teacher what she was doing to take advantage of her daughter's windows of opportunity before they closed. Unfortunately, according to Sousa, the teacher was unaware of the windows-of-opportunity research. He warns, "As the public learns more about brain research through the popular press, scenes like this are destined to be repeated, further eroding confidence in teachers and in schools."[29]

This well-established neuroscientific "finding" about a sensitive period for learning originated in the popular press and in advocacy documents. It is an instance where neuroscientists have speculated about the implications of their work for education and where educators have uncritically embraced that speculation. Presenting speculation as fact poses a greater threat to the public's confidence in teachers and schools than does Sousa's fifth-grade teacher.

During 1993, the *Chicago Tribune* ran Ron Kotulak's series of Pulitzer-Prize- winning articles on the new brain science. Kotulak's articles later appeared as a book titled *Inside the Brain: Revolutionary Discoveries of How the Mind Works*. Kotulak, an esteemed science writer, presented the first explicit statement that I have been able to find on the existence of a sensitive period between ages 4 and 10, during which children's brains learn fastest and easiest.[30] Variations on the claim appear in the Carnegie Corporation of New York's 1996 publication, *Years of Promise: A Comprehensive Learning Strategy for America's Children,* and in *Building Knowledge for a Nation of Learners*, published by the Office of Educational Research and Improvement of the U.S. Department of Education.[31]

A report released in conjunction with the April 1997 White House Conference on Early Brain Development stated, "[B]y the age of three, the brains of children are two and a half times more active than the brains of adults -- and they stay that way throughout the first decade of life. . . . This suggests that young children -- particularly infants and toddlers -- are biologically primed for learning and that these early years provide a unique window of opportunity or prime time for learning.32

If the sensitive period from age 4 to age 10 is a finding about which educators can be confident and one that justifies the current fuss about brain science, we would expect to find an extensive body of neuroscientific research that supports the claim. Surprisingly, brain-based enthusiasts appeal to a very limited body of evidence.

In Kotulak's initial statement of the sensitive-period claim, he refers to the brain-imaging work of Dr. Harry Chugani, M.D., at Wayne State University: "Chugani, whose imaging studies revealed that children's brains learned fastest and easiest between the ages of 4 and 10, said these years are often wasted because of lack of input."33

Years of Promise, the Carnegie Corporation report, cites a speech Kotulak presented at a conference on Brain Development in Young Children, held at the University of Chicago on 13 June 1996. Again referring to Chugani's work, Kotulak said that the years from 4 to about 10 "are the wonder years of learning, when a child can easily pick up a foreign language without an accent and learn a musical instrument with ease."34 *Years of Promise* also cites a review article published by Dr. Chugani that is based on remarks he made at that Chicago conference.35 *Rethinking the Brain*, a report based on the Chicago conference, also cites the same sources, as does the U.S. Department of Education document. What's more, Wolfe, Brandt, and Jensen also cite Chugani's work in their discussions of the sensitive period for learning.

A 1996 article on education and the brain that appeared in *Education Week* reported, "By age 4, Chugani found, a child's brain uses more than twice the glucose that an adult brain uses. Between the ages 4 and 10, the amount of glucose a child's brain uses remains relatively stable. But by age 10, glucose utilization begins to drop off until it reaches adult levels at age 16 or 17. Chugani's findings suggest that a child's peak learning years occur just as all those synapses are forming."36

To be fair, these educators are not misrepresenting Chugani's views. He has often been quoted on the existence and educational importance of the sensitive period from age 4 until age 10.37 In a review of his own work, published in *Preventive Medicine*, Chugani wrote:

> The notion of an extended period during childhood when activity-dependent [synapse] stabilization occurs has recently received considerable attention by those individuals and organizations dealing with early intervention to provide "environmental enrichment" and with the optimal design of educational curricula. Thus, it is now believed by many (including this author) that the biological "window of opportunity" when learning is efficient and easily retained is perhaps not fully exploited by our educational system.38

Oddly, none of these articles and reports cite the single research article that provides the experimental evidence that originally motivated the claim: a 1987 *Annals of Neurology* article.39 In that 1987 article, Chugani and his colleagues, M. E. Phelps and J. C. Mazziota, report results of PET (positron emission tomography) scans on 29 epileptic children, ranging in age from five days to 15 years. Because PET scans require the injection of radioactive substances, physicians can scan children only for diagnostic and therapeutic purposes; they cannot scan "normal, healthy" children just out of scientific curiosity. Thus the 1987 study is an extremely important one because it was the first, if not the only, imaging study that attempted to trace brain development from infancy through adolescence.

The scientists administered radioactively labeled glucose to the children and used PET scans to measure the rate at which specific brain areas took up the glucose. The assumption is that areas of the brain that are more active require more energy and so will take up more of 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.

One of their major findings was that, in all the brain areas they examined, metabolic levels reached adult values when children were approximately 2 years old and continued to increase, reaching rates twice the adult level by age 3 or 4. Resting glucose uptake remained at this elevated level until the children were around 9 years old. At age 9, the rates of brain glucose metabolism started to decline and stabilized at adult values by the end of the teenage years. What the researchers found, then, was a "high plateau" period for metabolic activity in the brain that lasted from roughly age 3 to age 9.

What is the significance of this high plateau period? To interpret their findings, Chugani and his colleagues relied on earlier research in which brain scientists had counted synapses in samples of human brain tissue to determine how the number and density of synaptic connections change in the human brain over our life spans. In the late 1970s, Peter Huttenlocher of the University of Chicago found that, starting a few months after birth and continuing until age 3, various parts of the brain formed synapses very rapidly.40 This early, exuberant synapse growth resulted in synaptic densities in young children's brains that were 50% higher than the densities in mature adult brains. In humans, synaptic densities appear to remain at these elevated levels until around puberty, when some mechanism that is apparently under genetic control causes synapses to be eliminated or pruned back to the lower adult levels.

With this background, Chugani and his colleagues reasoned as follows. There is other evidence suggesting that maintaining synapses and their associated neural structures accounts for most of the glucose that the brain consumes. Their PET study measured changes in the brain's glucose consumption over the life span. Therefore, they reasoned, as the density and number of synapses wax and wane, so too does the rate of brain-glucose metabolism. This 1987 PET study provides important indirect evidence about brain development, based on the study of living brains, that corroborates the direct evidence based on counting synapses in samples of brain tissue taken from patients at autopsy. In the original paper, the scientists stated an important conclusion: "Our findings support the commonly accepted view that brain maturation in humans proceeds at least into the second decade of life."41

However, if you read the 1987 paper by Chugani, Phelps, and Mazziota, you will not find a section titled "The Relationship of Elevated Brain Metabolism and Synaptic Densities to Learning." Neither Chugani nor any of his co-authors have studied how quickly or easily 5-year-olds learn as opposed to 15-year-olds. Nor have other neuroscientists studied what high synaptic densities or high brain energy consumption means for the ease, rapidity, and depth of learning.

To connect high brain metabolism or excessive synaptic density with a critical period for learning requires some fancy footwork -- or maybe more accurately, sleight of hand. We know that from early childhood until around age 10, children have extra or redundant synaptic connections in their brains. So, the reasoning goes, during this high plateau period of excess brain connectivity, "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."42 This, of course, is simply to assume that the high plateau period is a critical period.

Linking the critical period with learning requires an implicit appeal to another folk belief that appears throughout the history of the brain in education literature. This common assumption is that periods of rapid brain growth or high activity are optimal times, sensitive periods, or windows of opportunity for learning.43 We get from Chugani's important brain-imaging results to a critical period for learning via two assumptions, neither of which is supported by neuroscientific data, and neither of which has even been the object of neuroscientific research. The claim that the period of high brain connectivity is a critical period for learning, far from being a neuroscientific finding about which educators can be confident, is at best neuroscientific speculation.

Chugani accurately described the scientific state of affairs in his *Preventive Medicine* review. He *believes*, along with some educators and early childhood advocates, that there is a biological window of opportunity when learning is easy, efficient, and easily retained. But there is no neuroscientific evidence to support this belief. And where there is no scientific evidence, there is no scientific fact.

Furthermore, it would appear that we have a considerable amount of research ahead of us if we are to amass the evidence for or against this belief. Neuroscientists have little idea of how experience before puberty affects either the timing or the extent of synaptic elimination. While they have documented that the pruning of synapses does occur, no reliable studies have compared differences in final adult synaptic connectivity with differences in the experiences of individuals before puberty. Nor do they know whether the animals or individuals with greater synaptic densities in adulthood are necessarily more intelligent and developed. Neuroscientists do not know if prior training and education affect either loss or retention of synapses at puberty.44

Nor do neuroscientists know how learning is related to changes in brain metabolism and synaptic connectivity over our lifetimes. As the developmental neurobiologist Patricia Goldman-Rakic told educators, "While children's brains acquire a tremendous amount of information during the early years, most learning takes place after synaptic formation stabilizes."45 That is, a great deal, if not most, learning takes place after age 10 and after pruning has occurred. If so, we may turn into efficient general learning machines only after puberty, only after synaptic formation stabilizes and our brains are less active.

Finally, the entire discussion of this purported critical period takes place under an implicit assumption that children actually do learn faster, more easily, and more deeply between the ages of 4 and 10. There are certainly critical periods for the development of species-wide skills, such as seeing, hearing, and acquiring a first language, but critical periods are interesting to psychologists because they seem to be the exception rather than the rule in human development. As Jacqueline Johnson and Elissa Newport remind us in their article on critical periods in language learning, "In most domains of learning, skill increases over development."46

When we ask whether children actually do learn more easily and meaningfully than adults, the answers we get are usually anecdotes about athletes, musicians, and students of second languages. We have not begun to look at the rate, efficiency, and depth of learning across various age groups in a representative sample of learning domains. We are making an assumption about learning behavior and then relying on highly speculative brain science to explain our assumption. We have a lot more research to do.

So, despite what you read in the papers and in the brain-based education literature, neuroscience has *not* established that there is a sensitive period between the ages of 4 and 10 during which children learn more quickly, easily, and meaningfully. Brain-based educators have uncritically embraced neuroscientific speculation.

The pyramids were built by aliens -- to house Elvis.

A February 1996 article in *Newsweek* on the brain and education quoted Linda Darling-Hammond: "Our school system was invented in the late 1800s, and little has changed. Can you imagine if the medical profession ran this way?"[47] Darling-Hammond is right. Our school system must change to reflect what we now know about teaching, learning, mind, and brain. To the extent that we want education to be a research-based enterprise, the medical profession provides a reasonable model. We can only be thankful that members of the medical profession are more careful in applying biological research to their professional practice than some educators are in applying brain research to theirs.

We should not shrug off this problem. It is symptomatic of some deeper problems about how research is presented to educators, about what educators find compelling, about how educators evaluate research, and about how professional development time and dollars are spent. The "In Search of . . ." series is a television program that provides an entertaining mix of fact, fiction, and fantasy. That can be an amusing exercise, but it is not always instructive. The brain-based education literature represents a genre of writing, most often appearing in professional education publications, that provides a popular mix of fact, misinterpretation, and speculation. That can be intriguing, but it is not always informative. "In Search of . . ." is no way to present history, and the brain-based education literature is not the way to present the science of learning.

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