Education and the Brain: A Bridge Too Far

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Brain science fascinates teachers and educators, just as it fascinates all of us. When I speak to teachers about applications of cognitive science in the classroom, there is always a question or two about the right brain versus the left brain and the educational promise of brain-based curricula. I answer that these ideas have been around for a decade, are often based on misconceptions and overgeneralizations of what we know about the brain, and have little to offer to educators (Chipman, 1986). Educational applications of brain science may come eventually, but as of now neuroscience has little to offer teachers in terms of informing classroom practice. There is, however, a science of mind, cognitive science, that can serve as a basic science for the development of an applied science of learning and instruction. Practical, well-founded examples of putting cognitive science into practice already exist in numerous schools and classrooms. Teachers would be better off looking at these examples than at speculative applications of neuroscience.

The teachers' questions arise out of the perennial interest in the brain and neuroscience that has always existed at the margin of educational research and reform discussions. Recently, however, interest in how neuroscience might improve education has moved from the margins to center stage. Educators and education policy experts are the most vocal enthusiasts. Educational writers, likewise fascinated by the brain but puzzled by the mind, have picked up on this enthusiasm. Over the past year, there have been numerous books, journal articles, policy studies, and stories in the media about how our emerging understanding of brain development and neural function could revolutionize educational practice.[1] Neuroscientists, while interested in how their research might find application outside the laboratory and clinic, are more guarded in their claims. Often they are puzzled by the neuroscientific results educators choose to cite, by the interpretations educators give those results, and by the conclusions educators draw from them.

This article examines those results, interpretations, and conclusions—a set of claims that I will call the neuroscience and education argument. The negative conclusion is that the argument fails. The argument fails because its advocates are trying to build a bridge too far. Currently, we do not know enough about brain development and neural function to link that understanding directly, in any meaningful, defensible way to instruction and educational practice. We may never know enough to be able to do that. The positive conclusion is that there are two shorter bridges, already in

place, that indirectly link brain function with educational practice. There is a well-established bridge, now nearly 50 years old, between education and cognitive psychology. There is a second bridge, only around 10 years old, between cognitive psychology and neuroscience. This newer bridge is allowing us to see how mental functions map onto brain structures. When neuroscience does begin to provide useful insights for educators about instruction and educational practice, those insights will be the result of extensive traffic over this second bridge. Cognitive psychology provides the only firm ground we have to anchor these bridges. It is the only way to go if we eventually want to move between education and the brain.

The Neuroscience and Education Argument

The neuroscience and education argument relies on and embellishes three important and reasonably well-established findings in developmental neurobiology. First, starting in infancy and continuing into later childhood, there is a dramatic increase in the number of synapses that connect neurons in the brain. This synaptic proliferation (synaptogenesis) is followed by a period of synaptic elimination. Second, there are experience-dependent critical periods in the development of sensory and motor systems. Third, in rats at least, complex, or enriched, environments cause new synapses to form.

The argument runs as follows. Starting in early infancy, there is a rapid increase in the number of synapses or neural connections in children's brains. Up to age 10, children's brains contain more synapses than at any other time in their lives. Early childhood experiences fine-tune the brain's synaptic connections. In a process that we might describe as synaptic pruning, childhood experiences reinforce and maintain synapses that are repeatedly used, but snip away the unused synapses. Thus, this time of high synaptic density and experiential fine-tuning is a critical period in a child's cognitive development. It is the time when the brain is particularly efficient in acquiring and learning a range of skills. During this critical period, children can benefit most from rich, stimulating learning environments. If, during this critical period, we deprive children of such environments, significant learning opportunities are lost forever. As one popular article put it, "with the right input at the right

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time almost anything is possible," but "if you miss the window you're playing with a handicap" (Begley, 1996, p. 56).

Educators appeal to this argument to support a number of claims. E. D. Hirsch Jr. (Hirsch, 1996) uses it to argue that Jerome Bruner was actually correct to claim that any subject can be taught effectively in some intellectually honest form to any child at any stage of development. According to Hirsch, Bruner's claim now "represents the current thinking in mainstream neurobiology. 'Nature' is actually telling us something very different from the message carried by the phrase 'developmentally appropriate.' What nature is really saying about much learning much of the time is 'the earlier the better' " (p. 223). For Hirsch, neuroscience proves that "developmentally appropriate" are dirty words.

The claim that children are capable of learning more at a very early age, when they have excess synapses and peak brain activity, is one of the more common ones made in the neuroscience and education literature. Neuroscience implies that if information is presented in ways that fit each child's learning style, children are capable of learning more than currently believed (Education Commission of the States, 1996, p. vi). On this same evidence, other articles urge that children begin the study of languages, advanced mathematics, logic, and music as early as possible, possibly as early as age three or four. Parents should realize that they have a "golden opportunity to mold a child's brain. And that calls for a full-court press during the early years—that is, a rich child-care environment without undue academic stress" (Viadero, 1996, p. 32). Parents should become deeply involved in their children's early education because "when brain activity is high, parents have a unique opportunity to foster a love of learning" (Abelson, 1996, p. 1819). One journalist claims that, ideally, "at age 2½ or 3, children would start at Montessori school, where the educational program comes closer to matching neurological findings than any I know" (Beck, 1996, p. 23).

The neuroscientific evidence shows, according to a variety of educators, that there is a critical period for learning in early childhood that is somehow related to the growth and pruning of synapses. The ages for this critical period vary—birth to 3 years, birth to 6, birth to 10, 3 to 10. Educators cite this evidence to explain why some early childhood programs are more successful than others. Developmental neurobiology can explain why Head Start programs fail to result in sustained improvements in children's IQs. Head Start begins too late in children's critical learning period to rewire their brains (Begley, 1996, p. 56; Viadero, 1996, p. 33).

The neuroscience and education argument figures most prominently, however, in reports and policy studies, particularly to argue for the importance of early childhood education (Carnegie Task Force, 1996; Education Commission of the States, 1996; U.S. Department of Education, 1996). Among these reports, the Carnegie Task Force report, *Years of Promise*, has deservedly received the most attention. Early in that report, there is a synopsis of developmental neurobiology that formulates the neuroscience and education argument. Based on that argument, the report identifies the years from 3 to 10 as a critical period in child development. This is a primary theme in the report:

> [T]he age span from three to ten [is] absolutely crucial for children's optimal learning and development. These years offer families, communities, and schools critical intervention points for helping children develop knowledge and skills, positive attitudes toward learning, healthy behaviors, and emotional attachments of powerful and enduring significance. If these opportunities are squandered, it becomes progressively more difficult and more expensive to make up for the deficits later on. (Carnegie Task Force, 1996, p. 10)

What's wrong with this? In its synopsis, *Years of Promise* cites two neuroscience articles and a keynote address on brain development given by a science journalist. These are the only references to the neuroscience literature in the entire report. Yet, it contains hundreds of citations to the cognitive, developmental, and social psychology literature. This latter literature, not the neuroscience, provides evidence for the report's significant claims about the importance of early childhood. And, unfortunately, it has been primarily the neuroscience angle that commentators have seized on in their secondary discussions of the report. When I received a telephone inquiry from a journalist about the report, she wanted to know what I would advise parents about choosing a preschool based on what neuroscience tells us about brain development. My answer was brief: "Based on neuroscience, absolutely nothing."

We can't choose preschools based on neuroscience. Nor can we look to neuroscience as a guide to improved educational practice and policy. Our fascination with the brain leads us to overlook and underestimate what behavioral science can already provide to improve policy and practice. The neuroscience and education argument may be rhetorically appealing, but scientifically, it's a bridge too far. To see why, let's review what neuroscientists do know about synaptic growth, critical periods, and enriched environments.

Synaptogenesis

At birth, both nonhuman and human primate brains contain synapses that connect brain cells into circuits. Neonates have slightly fewer synaptic connections than do adults. However, early in postnatal development, the infant brain begins to form synapses far in excess of adult levels. This process of synaptic proliferation, called synaptogenesis, continues over a period of months that varies among species. This period of synaptic overproduction is followed by a period of synaptic elimination or pruning. This experience-dependent pruning process, which occurs over a period of years, reduces the overall number of synaptic connections to adult, mature levels, usually around the time of sexual maturity for the species. The mature nervous system has fewer synaptic connections than were present during the developmental peak. It is the pattern, rather than simply the number, of these connections that form the mature brain's neural circuitry and that support normal brain function.

Most of what we know about synaptogenesis and synaptic pruning comes from animal research, primarily from experiments on cats and monkeys. The original demonstration of overproduction and loss of synapses dates to 1975, when Brian Cragg found that in the cat visual system the number of synapses per neuron first increased rapidly and then gradually decreased to mature levels (Cragg, 1975a, 1975b). The neuroscience and education argument, however, more typically cites the later work of Goldman-Rakic and Rakic on synaptogenesis in rhesus monkeys (Goldman-

Rakic, 1987; Rakic, 1995). This work found that in rhesus monkeys, synaptic density (the number of synapses per unit volume of brain tissue) reaches maximal levels two to four months after birth and appears to do so simultaneously in all areas of the cerebral cortex. Then pruning begins. For rhesus, synaptic densities gradually decline to adult levels at around three years of age, the time of sexual maturity for that species.

In reviewing this work, readers outside the field should be aware of its complexity and the methodological issues involved. For example, measuring the number of synapses per neuron provides a more readily interpretable measure of synapse formation and loss than does synaptic density. Between birth and adulthood, the human brain increases in volume by a factor of three or four. Thus, if the number of synapses at birth remained constant, there would be a three- to four-fold drop in synaptic density due entirely to changes in brain volume during development. Readers should also be aware that whichever of these measures a study uses, we are measuring the aggregate number of synapses at any point in time. The measures reflect the number added less the number lost between the times of measurement. We know from other studies that different classes of neurons in the same brain region gain and lose synapses at different rates (Boothe, Greenough, Lund, & Wrege, 1979), and the same neurons can be adding synapses in one part of their dendritic field, while losing them in another part (Greenough & Chang, 1985). Thus, even the best measurements of synapses per neuron are only partial reflections of synapse loss and gain. Brain development at this level is a complex process indeed, and the studies we have to date give us only approximations to what is actually happening in the brain.

These difficulties aside, occasionally, one sees claims in the educational literature that the "critical period" in humans may be as early as from birth to age three years (Education Commission of the States, 1996). If based on neuroscience, this claim makes two assumptions. First, it assumes that the time course of synaptogenesis is the same for humans as it is for rhesus monkeys. Second, it assumes that the period of synaptic excess is the critical period for learning.

Unfortunately, there is comparatively little data on synaptogenesis in humans. Counting synapses in slices of monkey or human brain tissue is slow, tedious work. Furthermore, human studies are more difficult than animal studies because researchers can only obtain specimens of brain tissue for study at autopsy. What data there are suggest that synaptogenesis in humans follows a different time course. The human neonate has approximately 2.5×10^8 synapses per 100 mm³ of gray matter. In the visual cortex, there is a rapid increase in the number of synaptic connections at around 2 months of age, which reaches a peak at 8 to 10 months. Then there is a steady decline in synaptic density until it stabilizes at around 3.5×10^8 synapses / 100 mm³ at around age 10 years. Synaptic density in the visual cortex remains at this level throughout adult life (Huttenlocher, 1990).

Unlike the monkey, where synaptogenesis appears to occur simultaneously across all regions of the brain, the limited human data suggest that changes in the number of synapses per neuron or changes in synaptic density in our species may vary among brain areas. However, we have detailed data on only two regions of the human brain. Synap-

togenesis occurs very early in the human visual cortex, but in the frontal cortex, it appears to occur later and the pruning process takes longer. In the frontal cortex, synaptic densities do not stabilize at mature levels until mid- to late adolescence. This brain area, once thought not to be of much interest, is now thought to be the brain area responsible for planning, integrating information, and maintaining executive control of cognitive functions. Thus, what neuroscientists know about synaptogenesis does not support a claim that zero to three is a critical period for humans.

Whatever the time course of synaptogenesis in humans, if it has relevance for child development and education, we must be able to associate this neurodevelopmental change with changes in infants' behavior and cognitive capacities. What kinds of learning and development do neuroscientists think occurs during this time?

When neuroscientists discuss the behavioral correlates of synaptogenesis, they often cite changes in the behavior and cognitive capacities of monkeys. Again, this is not surprising because most of their research is on monkeys. When they extrapolate from the animal research to human infants, they typically rely on the same set of examples (Chugani, Phelps, & Mazziotta, 1987; Goldman-Rakic, 1987; Huttenlocher & de Courten, 1987). At the time synaptogenesis begins, at around 2 months of age, human infants start to lose their innate, infantile reflexes. At age 3 months, when synaptogenesis is well under way in the visual cortex, infants can reach for an object while visually fixating on it. At 4 to 5 months, infants' visual capacities increase. At 8 months, infants first show the ability to perform working memory tasks, such as Piaget's A–not B and delayed-response tasks. In these tasks, the infant watches while the experimenter places an object that interests the infant in one of two hiding wells in front of the infant. The experimenter covers both wells with identical covers, and for a period of 1 to 10 seconds, the experimenter prevents the infant from looking at or moving toward the correct well. Then the infant is allowed to reach for the object. In order to make a correct response, the infant must remember where the object was hidden. In A–not B, the experimenter continues to place the object in the same well until the infant makes several correct responses in a row. Delayed-response tasks are exactly the same, except that where the object is hidden varies randomly on each trial. Between 8 and 12 months of age, the time delay at which infants can succeed at this task increases steadily from a few seconds to 10 to 12 seconds. By 18 to 24 months of age, a time after which synaptogenesis has peaked at least in the visual cortex, children begin to use symbols, start to speak in sentences, and show spurts in vocabulary acquisition.

These examples are all significant developmental milestones that no doubt depend on brain development. We do know that these milestones are correlated with synaptogenesis (at least in the visual cortex), but that is all we know.

Educators should note two things, however. First, in all these examples, increases in synaptic density are correlated with the initial emergence of skills and capacities. These skills and capacities continue to improve after synaptic densities begin to regress to adult, mature levels. Some of these skills and capacities continue to improve after synaptic density reaches mature levels. Thus, the most we can say is that synaptogenesis may be necessary for the initial emergence of these abilities and behaviors, but it cannot account en-

tirely for their continued refinement (Goldman-Rakic, 1987). Some other form of brain maturation or change must contribute to this ongoing development. Some other neural mechanism must operate to support the significant learning that takes place after synaptogenesis and pruning cease.

Second, note that all these examples are examples of the emergence or changes in sensory, motor, and working memory functions. The development of vision, tactile discrimination, movement, and working memory are developmentally significant. However, these are not abilities and skills children learn in school or go to preschool to acquire. Normal children in almost any environment acquire these capacities at approximately the same age—children in affluent suburbs, children in destitute inner cities, children in rural-pastoral settings throughout the world. No doubt, in some way, the development of these capacities supports future learning. However, we have no idea, certainly no idea based on neuroscientific research, how the emergence of these capacities relates to later school learning or to the acquisition of culturally transmitted knowledge and skills. Synaptogenesis is a significant neurodevelopmental process that occurs in a variety of mammalian species, most likely for good evolutionary reasons. We do know from animal models that experience affects the pattern of synaptic connections and that it is the pattern, not just the number, of connections that matters for normal brain function. However, our current understanding of synaptogenesis can tell educators little, if anything, about what kinds of early childhood, preschool, or learning experiences might enhance children's cognitive capacities or their educational outcomes. Given what we know about this complex developmental process, it is premature, at best, to draw highly specific educational conclusions and recommendations from this knowledge.

Critical Periods

Research on critical periods has been prominent in developmental neurobiology for over 30 years. This research has shown that if an animal's sensory and motor systems—that is, systems like vision or tactile discrimination—are to develop normally, then the animal must have certain kinds of experiential input at specific times during its development. William Greenough, a neuroscientist at the University of Illinois, provides a useful way to think about this developmental phenomenon: It is as if evolution has resulted in neural systems that expect to find certain kinds of stimuli in the environment in order to fine-tune their performance (Greenough, Black, & Wallace, 1987).

In discussing critical periods, articles making the neuroscience and education argument often refer to the Nobel prize-winning research of David Hubel and Torsten Wiesel. They studied how visual deprivation affects the development of cats' visual systems. In their 1965 article, Hubel and Wiesel wrote, "In kittens, monocular or binocular deprivation by lid suture for the first three months of life leads to virtual blindness, marked morphological changes in the lateral geniculate body, and a severe deterioration of innate cortical connections" (Wiesel & Hubel, 1965, p. 1071). They also showed that the same or longer periods of complete visual deprivation had no such effects on the visual system of adult cats, nor on their ability to use the deprived eye, when it was subsequently reopened, to guide their behavior. For some educators and education writers, these rather drastic,

irreversible consequences of early sensory deprivation provide a vivid, compelling image to underscore the overwhelming importance of early childhood education.

In their experiments, Hubel and Wiesel sutured shut one eye of a cat or kitten, depriving the eye of all visual input. They were particularly interested to determine the effect of visual deprivation on what were assumed at that time to be innate cortical structures, ocular dominance columns. To test for the development of ocular dominance columns, Hubel and Wiesel recorded how neurons in the animals' visual cortex responded to visual stimuli presented to the normal eye and to the sutured eye after it was reopened. To simplify, let us assume that they recorded neural activity in the cat's left visual cortex. In a normal adult cat, the right (contra-lateral) eye activated around 20% of the cells from which they recorded. The left (ipsi-lateral eye) activated around 15% of the recorded cells. Around 65% of the cells responded to input from either eye. Monocular deprivation for periods between 3 and 16 months in adult cats had no effect on this pattern of ocular dominance. The cells responding exclusively to one or the other eye tended to occur in alternating patches that neuroscientists refer to as "columns."

Kittens responded differently. Newborn kittens deprived of visual input in one eye for two to three months after birth did not form normal ocular dominance columns. In these kittens, 85% of the cells from which Hubel and Wiesel recorded responded only to visual input from the open eye and approximately 15% of the cells responded to neither eye. In a second experiment, Hubel and Wiesel deprived kittens of visual input in one eye for two to three months and then performed a reverse suture, opening the deprived eye and suturing the open eye. They let the cats navigate their normal (laboratory) environment for periods up to a year. They found that this reverse-closure operation had no effect on recovery of either ocular dominance or visual function. Over 90% of the cells from which they recorded responded only to stimulation of the initially open eye. In both these experiments, Hubel and Wiesel reported that the kittens remained functionally blind in the initially deprived eye and could not use the eye to guide their behavior. Subsequent research suggested that some recovery is possible depending on the specific period of deprivation and the circumstances following deprivation (LeVay, Wiesel, & Hubel, 1980).

Already in 1972, however, there were indications that some recovery was possible. K. L Chow and D. L. Stewart (Chow & Stewart, 1972) deprived kittens of visual input to one eye for a period of one year after birth. They then did the reverse closure for an additional year. Rather than just letting the kittens navigate the laboratory environment, however, they subjected the kittens to a training regimen that forced them to use the initially deprived eye. Kittens forced to use the initially deprived eye showed some recovery. Chow and Stewart found that around 15% of the cells in the visual cortex responded to stimulation of the initially deprived eye, around 65% of the cells responded to stimulation of the initially open then deprived eye, and around 10% of the cells responded equally to stimulation of either eye. This is not a normal ocular dominance pattern, but it represents an improvement over the recovery reported in Wiesel and Hubel's article. Also, after the training regimen, the kittens regained sufficient function in the de-

prived eye to use it to guide their behavior. With appropriate training, kittens recovered function in the deprived eye well after the critical period originally described by Hubel and Wiesel.

The neuroscience and education literature reports Wiesel and Hubel's finding in statements like this: "When they removed the patches several weeks later, they found the kittens were blind in that eye. . . . The cats never did develop vision in those once-patched eyes" (Jones, 1995, p. 26). This both oversimplifies and misrepresents what we now know about critical periods in neural development.

Hubel and Wiesel launched an extremely important research program in developmental neurobiology that continues to this day. Over the past 30 years, this research program, engaging hundreds of neuroscientists, has advanced our understanding of critical periods. (See, for example, Daw, 1995.) Neuroscientists now understand that critical periods and synaptogenesis/synaptic pruning are related. Neural systems, particularly highly acute systems like vision, have evolved to depend on the presence of ubiquitous environmental stimuli to fine-tune their neural circuitry. These environmental stimuli maintain and re-enforce synapses that are repeatedly used to process them, while other synapses wither. This results in highly sensitive sensory systems. Generally, critical periods coincide with the period of excess synapse formation. Critical periods for neural systems end at or about the time when synaptic densities in the brain areas supporting that system stabilize at mature levels. During this time, some neural systems, like vision, are particularly sensitive to the presence or absence of general kinds of stimuli. Neuroscientists also know that there are different critical periods for specific functions. For example, within the visual system, there are different critical periods for ocular dominance, visual acuity, binocular function, and stereopsis (Daw, 1995). The human language function also seems to have several critical periods. Based on behavioral, not neuroscientific evidence, the critical period for phonology begins in infancy (Kuhl, 1994) and most probably ends around age 12. There also appears to be a lengthy critical period for acquiring syntax that ends at around age 16. In contrast to phonology and syntax, there is no critical period for learning the lexicon. Our ability to acquire new vocabulary continues throughout our lifetimes (Neville, 1995).

Neuroscientists know that it makes little sense to speak of *a* critical period for vision or for any other sensory system. Nor do they any longer interpret the critical period phenomenon as "a window nature temporarily throws open then slams shut." Rather, they now tend to interpret critical periods in terms of subtle, possibly gradual, changes in brain plasticity—changes in the brain's ability to be shaped and changed by experience that occur over the lifetime of the animal.

Neuroscientists now also think that for each specific function of a sensory system, like stereopsis in the visual system, there are three distinct phases within the critical period (Daw, 1995). First, there is a time of rapid change during which a function, like stereopsis, quickly reaches its mature processing level. This is followed by a second phase. During this phase, if the animal does not continue to receive appropriate sensory input from the environment, the system is still sufficiently plastic that deprivation can result in deterioration or loss of that function. After the period of sensitivity to deprivation, there seems to be a third phase of the critical period. During this phase, the system remains sufficiently plastic that appropriate sensory experience can compensate for deprivation and the animal can regain near-normal function. With appropriate training and therapy, at the appropriate time, cats, monkeys, and humans can recover near-normal visual function following periods of deprivation. How long critical periods and their phases last depends on the specific function and on the maturational timetable for the brain areas that support the function. Thus, to use our understanding of critical periods for therapeutic purposes requires both identifying specific component functions within a system like vision and possessing detailed knowledge about the maturation and development of particular brain areas. Neuroscientists are beginning to understand what some of these functions and areas might be for vision, but we know relatively little about critical periods for other sensory and motor systems.

As a result, all this very interesting neuroscience provides little guidance or insight for educators. Critical periods are related to synaptogenesis. As with synaptogenesis, we have evidence for the existence of critical periods only for component functions within sensory and motor systems and in humans for components of language. Currently, we do not know if critical periods do or do not exist for culturally transmitted knowledge systems—reading, arithmetic—that children acquire through informal social interaction and formal school instruction. We do not know what role synaptogenesis plays, if any, in the acquisition of these skills. Given our current state of neuroscientific understanding, however, we should be skeptical of claims that attempt to generalize from what we know about critical periods in brain development to critical periods for the acquisition of culturally transmitted knowledge.

If, as some neuroscientists think, over evolutionary time, primates and other mammals evolved to rely on environmental features to fine-tune highly sensitive neural systems, then these features are ubiquitous and available to any organism that inhabits any reasonably normal environment. Greenough calls this the "experience-expectant plasticity" of sensory and motor systems (Greenough, Black, & Wallace, 1987). The expected experiences must be present during certain developmental periods, but the expected experiences are of a very general kind—patterned visual input, the ability to move and manipulate objects, noises, the presence of speech sounds. These kinds of stimuli are available in any child's environment, unless that child is abused to the point of being raised in a sensory-deprivation chamber. In short, experience-expectant brain plasticity does not depend on specific experiences in specific environments, and for this reason, does not provide much guidance in choosing toys, preschools, or early child-care policies. The experiences children need to develop fundamental sensory-motor and language skills occur in any normal environment. This makes sense from an evolutionary perspective and from reflection on the cultural diversity in child-rearing practices around the world. If infants really needed highly specific experiences to become normal adults, the human race would be extinct. Cultural variations in child rearing suggest that there are many equally successful way to provide the normal environment needed for brain development.

Thus, we should be wary of arguments that use this neuroscientific evidence in arguments for highly specific early childhood environments, experiences, and policies. Despite what we see in the policy literature and read in the newspapers, as far as this developmental process is concerned, it matters little, if at all, whether the child is at home with Mom or in a Montessori preschool.

However, our understanding of critical periods does have one important implication for early childhood care: It is exceedingly important that parents and teachers identify and treat children's sensory problems—cataracts, eye misalignment, chronic inner ear infections—as early as possible. Even binocular focal disparity and severe astigmatism may have lasting effects. Normal fine-tuning cannot occur if the child cannot see, hear, or feel the ubiquitous environmental stimuli. And after the sensory problem is fixed, we must make sure—just like the kittens who were trained to use their once-deprived eye—that appropriate therapeutic experiences are available so that children can regain normal function.

Neuroscientific research on critical periods supports an educational moral or policy recommendation about the importance of diagnosing and treating children's sensory systems. It gives us relatively little specific guidance about how to design early childhood learning environments.

Enriched Environments and Synaptic Growth

The third theme in the neuroscience and education argument makes a claim, based on neuroscientific grounds, for the importance of enriched, stimulating early childhood environments. In support of this claim, proponents of the argument often cite the research of William Greenough and his colleagues (Greenough et al., 1987). Greenough raises rats in various environments and studies the effects of these environments on synapse formation in the rats' brains. In a series of experiments, he raised rats in what he calls "a complex environment." In a complex environment, several rats live together in large cages, filled with toys and obstacles. Greenough calls these environments complex—not enhanced or enriched—because he intends that a complex environment mimic rats' natural, wild environment. Complex environments are certainly enriched compared to typical laboratory rearing conditions. Usually laboratory rats are housed in individual cages or small group cages with no toys. Greenough has found that rats raised in complex environments are superior to their more austerely lab-reared mates on some learning tasks, like learning to run mazes. He and his colleagues have also found that rats raised in complex environments have 20% to 25% more synapses per neuron in the visual cortex. The rats also have more synapses per neuron in other brain areas, but the differences are not as large as those found in the visual cortex.

However, Greenough is careful in interpreting his findings. First, he argues that the synapse formation that occurs as a result of living in a complex environment is largely not a critical-period phenomenon. The kind of brain plasticity that arises from rearing in a complex environment seems to rely on a neural mechanism that is very different from the pruning mechanism that gives rise to critical periods. Rearing in a complex environment, on Greenough's interpretation, causes new synapses to form in response to new and varied experiences. Second, although his original experiments were done on newborn rats, in subsequent studies,

Greenough and his colleagues showed that even the brains of mature, adult rats form new synapses in response to new experiences. Unlike critical-period phenomena, the ability to create new synapses in response to new experiences seems to persist throughout the animal's life span.

Greenough's work suggests that there is a second kind of brain plasticity. Whereas synaptogenesis and critical periods figure in experience-expectant plasticity, Greenough characterizes synaptic growth in complex environments as experience-dependent plasticity. Experience-dependent plasticity allows an organism to acquire knowledge that is specific to its own environment. It allows an organism to learn about features of the particular environment that it inhabits, environmental features that are not ubiquitous for the entire species. For example, an animal must learn where to find water, food, and shelter in its environment. It must learn to recognize significant conspecifics—its mother, its siblings, the dreaded alpha male. Humans also have to learn these kinds of things, along with the specifics of our surrounding culture. We must also learn the particular, specific features of our native languages. Among the particular, specific features that vary widely depending on the sociocultural niche we inhabit is vocabulary. Our brain's experience-dependent plasticity allows us to acquire knowledge of these specifics throughout our lives.

Thus, research on the effects of complex environments on the brain is exceedingly interesting and important because it does begin to link learning with synaptic change and brain plasticity. It points to a kind of brain plasticity that is present throughout the animal's lifetime. This kind of plasticity allows the animal to learn from experience. It allows the animal to acquire knowledge about an environment and to use that knowledge to solve novel problems that arise in that environment. It allows the animal to become more expert in negotiating its environment. This kind of brain plasticity, unlike synaptogenesis and critical periods, might eventually provide a neural basis for the informal and formal learning that goes on in our sociocultural environments, including our schools.

This presents an intriguing possibility and one that is seductive for both educators and journalists. However, educators should be cautious in interpreting this work and in thinking about how it might inform policy and practice. A recent journalistic treatment of this research illustrates three things educators should keep in mind when considering the implications of research on complex environments.

On the cover of the October 1996 issue of *Tennis USTA*, a publication of the United States Tennis Association, the question, "Can tennis build brain power?," appeared under a picture of Gardner Mulloy. Mulloy is 82 years old and the winner (at last count) of 108 USTA Championships. A caption described him as "Fit and feisty at 82." An article inside titled "Tennis and the Brain" briefly reviewed the research on what happens to rats reared in complex environments and gave an affirmative answer to the question on the cover. Sports that involve strategy stimulate brain-cell growth and stave off the brain's aging process, the writer concluded. Gardner Mulloy—fit, feisty, and 82—is living proof.

Although educators and neuroscientists might want to dispute the particulars of this journalistic treatment, the Gardner Mulloy and tennis example provides some useful reminders in thinking about complex environments. First,

complex environment research is often cited as evidence for the critical importance of early childhood environments, particularly in the years from birth to three. Gardner Mulloy provides a useful reminder that the research does not support such a simple conclusion. Although the effects of complex environments may occur more readily in younger animals, the effects do occur throughout the life span. Older animals learn, too. How we learn might change as we develop and mature, but the research does indicate that we learn and that the brain remains plastic throughout our lives. If so, we should be wary of arguments from the effects of complex environments to the conclusion that there should be a selective educational focus on children's earliest years.

Second, we should note that *Ceramics* magazine could have run the same article, "Ceramics and the Brain," with an accompanying profile of Beatrice Woods "Throwing and thriving at 104." *Muscle Magazine, Field and Stream,* and, possibly, *Country Living* could run similar articles featuring the appropriate mature practitioner. Not only are we life-long learners, but we can learn a myriad of things, all of which no doubt affect our brains, all of which increase our brain power if we are willing to equate brain power with synaptic growth. The reminder here is that the neuroscientific evidence points to the existence of a general neural mechanism that contributes to life-long brain plasticity and, presumably, to learning. Although this is intriguing, the finding provides little insight into how to teach tennis, ceramics, reading, or algebra. This research does not yet provide much guidance in our attempts to answer the fundamental educational question: How should we design instruction—how should we design complex, pedagogical environments—to optimize learning in any domain for children or adults?

Finally, that the article appeared in a tennis magazine in itself provides a useful reminder. Tennis is an upscale, largely middle-class activity. However, we should remind ourselves that we should be careful about drawing inferences from the existence of a general neural mechanism to what subjects and skills children, or adults, should learn. In appealing to this research, advocates move too easily from "complex" to "enriched," where "enriched" is very much in the eye of the beholder, often reflecting the beholder's cultural and class values. Rich, complex environments tend to include what the authors value and exclude what they abhor—*Sesame Street* but no other television, music lessons, athletics of the right kind, early math instruction, attending the right preschool, and having the right toys. Complex, enriched environments for humans end up having many of the features of upper-middle class, urban, and suburban life—Gardner Mulloy and *MisterRogers'* neighborhoods. We may have reasons to prefer Latin to Ebonics, Mozart to Buddy Guy, tennis to bowling, and suburbs to inner cities, but, we should remind ourselves, neuroscience does not provide the reasons.

Despite its popularity, the neuroscience and education argument does not offer much support for the conclusions and recommendations its advocates attempt to draw from it. What we know about synaptogenesis, critical periods, and complex environments cannot provide much guidance for educational policy, classroom practice, or early childhood education. The primary reason the argument fails is that it attempts to link what happens at the synaptic level in

the brain to development, learning, and instruction. We simply do not know enough about how the brain works to draw educational implications from changes in synaptic morphology. We do not know how synaptic change supports learning. There is a gaping chasm between our understanding of what happens to synapses as a result of experience and what happens or should happen in preschool or third grade. The neuroscience and education argument attempts to bridge this chasm by drawing educationally relevant conclusions from correlations between gross, unanalyzed behaviors—learning to read, learning math, learning languages—and poorly understood changes in brain structure at the synaptic level. This is the bridge too far. Our emerging understanding of the brain may eventually be able to contribute to education, but it will require us, at least initially, to take a different, less direct route, a route that links brain structures with cognitive functions and cognitive functions with instructional goals and outcomes.

Mind, Brain, and Education

If we cannot build the neuroscience and education bridge, but are interested in how brain structure supports cognitive function, we can pursue a more promising strategy that involves traversing two existing spans. The first connects educational practice with cognitive psychology, and the second connects cognitive psychology with brain science.

Cognitive psychology is the study of mind and mental function, a study not necessarily concerned with brain structure and function. Cognitive scientists attempt to discover the mental functions and processes that underlie observed behavior. They attempt to analyze those functions into even more elementary cognitive operations. For example, cognitive scientists analyze reading into a set of component cognitive skills that include word recognition, grammatical processing, text modeling, and metacognitive monitoring. In turn, they analyze word recognition into more elementary cognitive operations of initial encoding—forming a visual representation of the printed word—and lexical access—determining if the visual representation matches a word in the reader's language. In an educational context, this analytic method helps us understand the component processes, skills, and knowledge structures that underlie expertise in domains like reading, mathematics, writing, and science. Cognitive psychology already has a justified claim to be the basic science of learning and teaching (Bruer, 1993) and has contributed to the design of effective instructional tools (McGilly, 1994). Although some might wish that more educators traveled it, there already is a bridge between cognitive psychology and educational practice.

This same analytic method also supports a bridge between cognitive psychology and one area of neuroscience—cognitive neuroscience. Cognitive neuroscientists work at the mind-brain interface, at the interface between biological and behavioral science. One thing they do as biological scientists is use brain imaging and recording techniques to capture and analyze brain activity. As behavioral scientists, they use the methods and models of cognitive psychology to identify and analyze cognitive functions that guide human behavior. These cognitive analyses and models allow cognitive neuroscientists to formulate informative, testable hypotheses about how brain structures implement the mental functions that underlie learning and intelligent

behavior. Fortunately, cognitive analyses and models provide candidate mental functions that occur at levels of temporal (seconds to milliseconds) and spatial (millimeters) resolution that best exploit the power of current imaging and recording technologies. In contrast, synaptic change occurs at spatial resolutions on the order of ten thousandths of a millimeter. At this much lower level of temporal and spatial resolution, cognitive neuroscientists are beginning to identify the neural correlates and circuits that underlie specific cognitive functions.

Among brain imaging technologies, the best known and most widely used are Positron Emission Tomography (PET) and functional Magnetic Resonance Imaging (fMRI). PET can measure changes in cerebral blood flow, oxygen utilization, and glucose utilization that are linked to neural activity. fMRI measures changes in the ratio of oxygenated to deoxygenated hemoglobin that, through a longer chain of reasoning, can also be linked to neural activity. Both allow cognitive neuroscientists to make images of these changes in normal human brains as subjects perform cognitive tasks. PET and fMRI have a spatial resolution in the millimeter range, but a temporal resolution of, at best, seconds. These methods allow us to see how cognitive tasks change brain activity at the level of cortical columns to cortical maps, brain structures that contain millions of synapses. However, because these technologies have relatively poor temporal resolution, they can tell us little about the timing and sequencing of the component processes in a cognitive task. For example, consider skilled reading. A skilled reader fixates and processes one word every 250 milliseconds. In a quarter of a second, a skilled reader can identify a word in a text, assign the word a meaning and grammatical role, integrate the word into a grammatical structure for the sentence it occurs in, and incorporate an interpretation of that grammatical structure into a mental model of the "gist" of the text. Thus, imaging techniques like PET and fMRI can helping us localize, one by one, areas of brain activity that underlie the various cognitive components of reading; they cannot give us a picture, as yet, of how these areas interact during reading. The limited temporal resolution (at best, seconds) of these technologies cannot tell us much about the temporal dynamics of the brain processes that underlie skilled reading because in skilled reading, too much happens in one or two seconds.

Brain recording techniques like electroencephalography (EEG), event-related potentials (ERP), and magnetoencephalagraphy (MEG) measure the electric or magnetic fields that neural activity generates at the scalp surface. These methods have a temporal resolution in the millisecond range, but a spatial resolution of only centimeters. These techniques allow accurate timing of changes in brain activity during a cognitive task, but can localize that activity with a precision only in the range of tens to hundreds of millimeters, often only to the level of hemispheric regions. Thus, using cognitive models and analyses in imaging and recording experiments, cognitive neuroscientists can map elementary cognitive operations, occurring on a time scale between milliseconds and seconds, onto brain structures that range in size from hemispheric regions (centimeters) to cortical columns (millimeters).

The following example illustrates how cognitive psychology can begin to link educational questions with cognitive neuroscience. The example presents two pieces of research on numerical cognition. The first piece of research addresses an educational problem. Sharon Griffin, Robbie Case, and Bob Siegler applied the methods of cognitive psychology to analyze the cognitive skills and knowledge children must have to succeed in learning elementary arithmetic (Griffin, Case, & Siegler, 1994). They found that the ability to do numerical comparisons—which is bigger, 5 or 7?—is one such skill. They also found that some children from low-SES homes may not acquire this skill before entering school, but with appropriate instruction, they can acquire it. Their work is but one example of a bridge that exists between cognitive psychology and instruction. The second piece of research is from the field of cognitive neuroscience. Using a model that analyzes the numerical comparison skill into its subcomponents, Stanislas Dehaene conducted a series of brain-recording experiments to trace the neural circuitry involved in making such comparisons (Dehaene, 1996). This is an example of a second bridge that is now being rapidly built between cognitive psychology and systems neuroscience, a bridge that will help us understand how brain structures implement cognitive functions. Cognitive psychology, a behavioral science committed to the analysis and scientific study of our mental capacities, is not only making fundamental contributions to educational practice and our understanding of the brain, but also provides the intermediate level of analysis we need if we are ever to link brain and education.

The First Bridge: Instruction to Cognition

First, let's consider how cognitive psychology has contributed to the solution of an educational problem. Improving mathematics instruction is an acknowledged educational problem for American schools. In the most recent such study, the Third International Mathematics and Science Study, U.S. eighth-grade students scored below the international average in mathematics. In 20 of the 41 countries surveyed, the average performance was significantly better than the average performance of U.S. students. In 13 countries, average performance was not significantly different from that in the U.S. The U.S. average student performance in mathematics was significantly better than that of only 7 nations (Mathematics Achievement, 1996). Furthermore, the National Assessments of Educational Progress (NAEP) in mathematics reveals an additional, serious problem within the United States. Since the first NAEP math assessment in 1978, Black and Latino/a students have improved consistently over the years on this assessment, while scores for White students have remained relatively stable. Nonetheless, minority students still score significantly below their White majority counterparts. On the 1994 NAEP math assessment, the average mathematics score for White 9-year-olds was 237, compared to 212 for Black 9-year-olds and 210 for Latino/a 9-year-olds (Campbell, Reese, O'Sullivan, & Dossey, 1994, p. 55). On tests of numerical concepts, significant numbers of children attending kindergarten in low-income, inner-city communities did not demonstrate number knowledge comparable to that of their middle-income peers (Case & Griffin, 1990). These initial differences tend to increase, rather than disappear, during the elementary school years (NSF Survey, 1988). If it were possible to eliminate these differences at school entry, many fewer students would be at risk for math failure and many more might successfully complete the elementary

school mathematics curriculum. How might we change the arithmetic and number skills curricula in kindergarten and first grade to eliminate these differences? Cognitive and developmental psychologists have helped us answer this question.

Over the past 20 years, cognitive and developmental psychologists have delineated the basis and emergence of numerical cognition. Humans, like other animals, possess an innate, preverbal sensitivity to quantity. Building on this innate sensitivity, by age two to three years, human infants begin to learn the number names in their native language and to use these number names in counting-like activities and games. By age three or four years, most children can compare two small numbers for size and reliably determine which is larger and which is smaller. Soon after, they are able to coordinate their counting and comparing skills to invent counting strategies for solving simple arithmetic problems. Among these invented strategies are the well-known counting-up, counting-on, and min strategies. Before entering school, most children also learn Arabic numerals and become adept at using their invented strategies to learn basic number facts. Most children seem to acquire these rudiments of numerical cognition informally, before they begin formal arithmetic instruction in kindergarten or first grade.

Robbie Case, Sharon Griffin, and Bob Siegler characterized this informally acquired number knowledge as the central conceptual structure that is a necessary prerequisite for learning formal arithmetic in the early elementary grades (Griffin, Case, & Siegler, 1994). Children who possess this central conceptual structure have what Case, Griffin, and Siegler call a "mental number" and the rudiments of number sense. Children who have this conceptual structure know the number names in their language, know that when one counts it is necessary to assign one number name and only one number name to each object, and know that the number names occur in a fixed order. They know that the number names refer to set sizes and know that as one moves up (down) through the number names in the counting process, each number name refers to a set that has one more (less) object in it then the previously named set. They also understand that the Arabic numerals are alternative written symbols they can use to name set sizes.

Griffin and Case's "Rightstart" curriculum (more recently renamed "Number Worlds") attempts to teach this conceptual structure—to teach number sense—to kindergarten, first, and second-grade students (Griffin, Case, & Siegler, 1994). The curriculum meets the special needs of children who may not have acquired the mental number line before entering school. Most children acquire this conceptual structure informally through interactions with parents and siblings before they enter kindergarten. Children who have not acquired it require formal instruction to do so. The kindergarten Number Worlds curriculum explicitly teaches the number-word sequences from 1 to 10 and 10 to 1, the one-one correspondence rule fundamental to counting, and that numbers name set sizes. It teaches the incrementing and decrementing rules on the number line—i.e., that moving up (down) the number line in increments of 1 is equivalent to adding (subtracting) 1. The curriculum teaches that the Arabic numerals are alternate names for the numbers. Finally, it explicitly teaches children how to compare numbers for size.

Griffin and her colleagues evaluated the Number Worlds curriculum in Worcester, MA, public schools (Griffin & Case, 1993). Using a diagnostic test for number knowledge, they identified a group of entering kindergarten students who scored below criterion on the test and were thus judged at risk for failing their first formal arithmetic instruction. These students all attended neighborhood schools in Worcester, and most of them were from low-income homes. Half of these children received the Number Worlds curriculum and half, the control group, received the school system's standard early math curriculum. Griffin also identified a group of students who attended a city-wide magnet school and who scored well on the diagnostic test. These students were a normative group, who could be expected to achieve at or above levels one could reasonably expect in a public school system.

On entering kindergarten, the Number Worlds and control group students scored significantly below the expected kindergarten score of 9 to 11 points on the number knowledge test. The students in the normative group scored at or above the criterion on kindergarten entry. After one year of Number Worlds instruction, scores on the number knowledge test for the Number Worlds students did not differ significantly from normative group's scores. Students in the control group, however, still lagged significantly behind. After an additional year of Number Worlds in grade one, the treatment and normative groups were again indistinguishable, scoring at or above the criterion on the number knowledge test. The control group still lagged significantly behind.

One might argue that this evaluation identified children on the basis of poor performance on the number knowledge test, taught them skills needed to pass the test, and then tested them again with the same instrument. Other assessments, however, showed that the Number Worlds children also improved significantly compared to the control group students on tasks and problems usually encountered in first grade arithmetic. In fact, the Number Worlds children scored significantly higher than even the normative group on solving word problems, expressing numerical relations in number stories, and doing successive mental arithmetic operations. In another series of tests, the three groups received the first 20 questions from a test of number skills used in a crossnational comparative study (Stevenson, Yee, & Stigler, 1986). On this test, the Number Worlds children outperformed the normative group by a considerable margin, and their performance exceeded or equaled that of Japanese students on this test. After two years in this cognitively based curriculum, students known to be at risk for failing early arithmetic performed at world-class levels on this test of number skills.

The Number Worlds curriculum, now undergoing further refinement and evaluation in Worcester and in other cities, is an example of a how a detailed understanding of numerical cognition can help solve an educational problem. It is based on a cognitive model that specifies the component skills and pieces of number knowledge children must possess and coordinate if they are to have number sense and succeed at early mathematics instruction. The Number Worlds curriculum builds a bridge between cognitive psychology and educational practice.[2]

The detailed cognitive model provided an informed basis for the diagnostic number knowledge test Griffin and Case

used in the Number Worlds project. It allowed them to determine which component numerical skills and knowledge facets children had or had not acquired before entering kindergarten. Individual test items tapped students' knowledge of the number names, their ability to count, their ability to compare numbers for size, and their ability to solve simple arithmetic problems (presumably by coordinating their counting and comparing skills). In pilot studies to norm this test, the research team discovered, to its surprise, that there were significant differences in children's test performance based on their families' socioeconomic status. Among entering kindergarten students, there were relatively small differences in the ability to count, compare, and add sets of visible, physically present objects. However, when children were asked to solve similar problems mentally, using only verbal statements of the problem, lower-SES children scored significantly below higher-SES children. This difference was most pronounced on the numerical comparison task. On questions like, "Which number is bigger, 5 or 4?," 96% of high-SES children could answer correctly, but only 18% of low SES-children could do so (Griffin, Case, & Siegler, 1994, p. 31). Numerical comparison was the component skill that most distinguished the high-SES, math-ready children from the low-SES, at-risk children. The Number Worlds curriculum taught numerical comparison explicitly and was most successful in imparting this skill to the at-risk children, who, for some reason, had failed to acquire it at the "normal" age seen in most middle-class children. The cognitive psychologists' analysis of numerical cognition into its component skills revealed that numerical comparison plays a crucial role in children's ability to benefit from formal arithmetic instruction on school entry.

The Second Bridge: Cognition to Neural Circuitry

Numerical comparison is but a single, albeit important, skill within numerical cognition. It is at this level of analysis, however, that cognitive neuroscientists are beginning to understand how neural structures and brain circuits implement cognitive processes. Using cognitive models and brain recording techniques, they can begin to trace the neural circuitry involved in a skill like numerical comparison.

Cognitive psychologists have further analyzed numerical comparison into its subcomponents and developed cognitive models of this process. One simple model analyzes numerical comparison into three stages. First, there is an identification stage in which the subject identifies the input stimuli. Second, there is a magnitude comparison stage in which the subject judges which of the stimuli is larger or smaller. Third, there is a response stage in which the subject prepares and executes a verbal or motor act to indicate his or her answer to the comparison question. This is a serial model of numerical comparison. It assumes that three stages occur one after the other and that processing in a later stage does not influence processing in an earlier stage.

Cognitive psychologists have methods to assess the validity of a serial stage model that rely only on behavioral data. One of these methods is the Additive Factors Method. If a serial model is correct, then altering a factor that affects only one stage of the process—here, either identification, comparison, or response—should influence subjects' reaction times only for that processing stage.

Stanislas Dehaene (Dehaene, 1996) designed such an experiment to test this serial model of numerical comparison.

In his experiment, right-handed college students had to decide if a number flashed on a computer screen was larger or smaller than five, then press a key to indicate their response. Dehaene manipulated three independent factors, where each factor was assumed to influence processing within only one of the model's stages. For the stimulus identification stage, he contrasted subjects' performance when given Arabic (1, 4, 6, 9) versus verbal notation (one, four, six, nine). For the magnitude comparison stage, he compared subjects' performance on close (4, 6 and four, six) versus far (1, 9 and one, nine) comparisons to the standard 5. His reason for choosing this factor is the well-established distance effect (Moyer & Landauer, 1967). The distance effects shows that it takes subjects longer, and they make more errors, when asked to compare numbers that are close in numerical value than when asked to compare numbers that are farther apart in numerical value. In Dehaene's experiment, half the comparisons were close comparisons and half were far comparisons, a factor that should affect only the magnitude comparison stage. Finally, on half the trials, subjects had to respond "larger" using their right hand and "smaller" using their left hand, and on half the trials, "larger" with their left and "smaller" with their right. This factor should influence reaction times only for the motor preparation and execution stage.

When Dehaene analyzed subjects' reaction times on the numerical comparison task, he found that the overall median (correct) reaction time was around 400 milliseconds. Subjects needed less than one half second to decide if a number was greater or less than 5. Furthermore, he found that each of the three factors had an independent influence on reaction time. Reactions to Arabic stimuli were 38 milliseconds faster than those for verbal notation, far comparisons were 18 milliseconds faster than close comparisons, and right-hand responses were 10 milliseconds faster than left-hand responses. Finally, the three factors had an additive effect on subjects' total reaction times, just as one would expect if subjects were using the serial-processing model.

Dehaene's experiment, however, went beyond the typical cognitive experiment that would have stopped with the analysis of reaction times. Dehaene also recorded event-related potentials (ERPs), while his subjects performed the number comparison task. His ERP system measured electrical currents emerging from the scalp at 64 sites, currents that presumably were generated by the electrical activity of large numbers of nearby neurons. Recall that ERPs have relatively poor spatial resolution, but relatively precise temporal resolution. Significant changes in the electrical activity recorded at each of the 64 sites as subjects compared numbers might give general indications about where the neural structures were in the brain that implemented the three processing stages. The ERPs' more precise temporal resolution might indicate the time course of the three processing stages. Together, the spatial and temporal data would allow Dehaene to trace, at least approximately, the neural circuitry that is active in numerical comparison. A cognitive model together with brain recording techniques created the possibility of mapping sequences of elementary cognitive operations onto their underlying neural structures and circuits.

This first significant ERP effect Dehaene observed occurred 100 milliseconds after the subjects saw either the Arabic or verbal stimulus. This change in brain activity was

not influenced by any of the experimental factors. It appeared to occur in the right posterior portion of the brain. Based on this and other imaging and recording experiments, early activation in that part of the brain is most likely the result of the brain's initial, nonspecific processing of visual stimuli.

At approximately 146 milliseconds after stimulus presentation, Dehaene observed a notation effect. When subjects processed number words, they showed a significant negative electrical wave on the electrodes that recorded from the left posterior occipital-temporal brain areas. In contrast, when subjects processed Arabic numerals, they showed a similar negative electrical wave on electrodes recording from both the left and right posterior occipital-temporal areas. This suggests that number words are processed primarily on the left side of the brain, but that Arabic numerals are processed on both the left and right sides.

To look for a distance effect and the timing and localization of the magnitude comparison stage, Dehaene compared the ERPs for digits close to 5 (4, four and 6, six) with the ERPs for digits far from 5 (1, one and 9, nine). This comparison revealed a parieto-occipto-temporal activation in the right hemisphere that was associated with the distance effect. This effect was greatest approximately 210 milliseconds before the subjects gave their responses. What is significant here, according to Dehaene, is that the timing and distribution of the electrical currents was similar for both Arabic digits and verbal numerals. This supports the claim, Dehaene argues, that there is a common, abstract, notation-independent magnitude representation in the brain that we use for numerical comparison. To make a numerical comparison, we apparently translate both number words and Arabic digits into this abstract magnitude representation.

Finally, Dehaene found a response-side effect that occurred approximately 332 milliseconds after the stimulus or equivalently 140 milliseconds before the key press. This appeared as a substantial negative wave over motor areas in the brain. The motor area in the left hemisphere controls movement of the right side of the body, and the motor area in the right hemisphere controls movement of the left side of the body. Thus, as expected, this negative wave appeared over the left hemisphere for right-hand responses and over the right hemisphere for left-hand responses.

Dehaene's experiment exemplifies how cognitive neuroscientists use cognitive theories and models in brain imaging and recording experiments. Well-designed, interpretable imaging and recording studies demand analyses of cognitive tasks, construction of cognitive models, and use of behavioral data, like reaction times, to validate the models. Experiments like these suggest how neural structures implement cognitive functions, tell us new things about brain organization, and suggest new hypotheses for further experiments.

Dehaene's experiment traces the approximate circuitry the brain uses to identify, compare, and respond to number stimuli. The experiment reveals several new things about brain organization that suggest hypotheses for further experiments. First, the experiment points to a bilateral neural system for identifying Arabic digits. This is something that one could not discover by analyzing behavioral data from normal subjects. Nor is it a finding neuropsychologists' studies of patients with brain lesions and injuries could re-

liably and unambiguously support. In fact, Dehaene suggests, the existence of such a bilateral system could explain some of the puzzling features about the patterns of lost versus retained number skills neuropsychologists see in these patients. Second, this experiment suggests there is a brain area in the right hemisphere that is used in numerical comparison. This area might be the site of an abstract representation of numerical magnitude, a representation that is independent of our verbal number names and written number symbols. This, too, runs counter to common neuropsychological wisdom. Neuropsychologists commonly hold that the left parieto-occipito-temporal junction, not the right, is the critical site for number processing because damage to this area in the left hemisphere causes acalculia. Dehaene's finding of right hemisphere involvement during the comparison phase suggests that neuropsychologists should look more carefully than they might have in the past at numerical reasoning impairments among patients who have suffered damage to the right posterior brain areas. They might find, for example, patients who are able to read Arabic numerals and perform rote arithmetic calculations, but who are unable to understand numerical quantities, make numerical comparisons, or understand approximate numerical relations.

Dehaene's work is just one example of how cognitive neuroscience is advancing our understanding of how brain structures might support cognitive function. Cognitive neuroscientists at numerous institutions are starting to trace the neural circuitry for other cognitive constructs and culturally transmitted skills. Several studies suggest that automatic and controlled processing rely on distinct brain circuits (Raichle et al., 1994). Other studies show how attention can reorder the sequence in which component cognitive skills are executed in a task: The areas of brain activation remain the same, but the sequence in which the areas become active changes (Posner & Raichle, 1994, ch. 6). We are beginning to understand the different brain systems that underlie language processing and their developmental time course (Neville, 1995). Using our rather detailed cognitive models of reading—particularly word recognition—PET, fMRI, and ERP studies allow us to trace the neural circuitry for early reading skills and to document the developmental course of this circuitry in children between the ages of 5 to 12 years (Posner, Abdullaev, McCandliss, & Sereno, in press).

However, in most cases, we are still far from understanding how these results might contribute to advances in the clinic, let alone in the classroom. It is not yet clear how we move from results like these across the bridge to educational research and practice. The example does, however, make two things clear. First, there is no way that we could possibly understand how the brain processes numbers by looking at children's classroom or everyday use of numbers or by looking at math curricula. Second, there is no way we could possibly design a math curriculum based on Dehaene's results. It is the cognitive research, exemplified here by the work of Griffin, Case, and Siegler, that creates both of those possibilities.

When we do begin to understand how to apply cognitive neuroscience in instructional contexts, it is likely that it will first be of most help in addressing the educational needs of special populations. Cognitive psychology allows us to understand how learning and instruction support the acquisi-

tion of culturally transmitted skills like numeracy and literacy. Cognitive psychology in combination with brain imaging and recording technologies also allows us to see how learning and instruction alter brain circuitry. It opens the possibility of being able to see and to compare these learning-related changes in normal-versus-special learning populations. Such comparative studies might yield insights into specific learning problems and, more importantly, into alternative, compensatory strategies, representations, and neural circuits that children with learning disabilities might exploit. These insights could in turn help us develop better instructional interventions to address specific learning problems.

Conclusion

The brain does and should fascinate all of us, and we should find advances in neuroscience exciting. As educators, we should also be interested in how basic research might contribute to and improve educational practice. However, we should be wary of claims that neuroscience has much to tell us about education, particularly if those claims derive from the neuroscience and education argument. The neuroscience and education argument attempts to link learning, particularly early childhood learning, with what neuroscience has discovered about neural development and synaptic change. Neuroscience has discovered a great deal about neurons and synapses, but not nearly enough to guide educational practice. Currently, the span between brain and learning cannot support much of a load. Too many people marching in step across it could be dangerous.

If we are looking for a basic science to help guide educational practice and policy, cognitive psychology is a much better bet. It already is helping us solve educational problems and design better instructional tools. Cognitive psychology, in the hands of cognitive neuroscientists, is also fundamental to our emerging understanding of how neural structures support and implement cognition functions. If, in the future, brain research does contribute to educational practice, it will most likely do so via the indirect, two-bridge route, not the direct one espoused in the neuroscience and education argument.

Looking to the future, we should attempt to develop an interactive, recursive relationship among research programs in education, cognitive psychology, and systems neuroscience. Such interaction would allow us to extend and apply our understanding of how mind and brain support learning. In the meantime, we should remain skeptical about brain-based educational practice and policy, but look more carefully at what behavioral science already can tell us about teaching, learning, and cognitive development.[3]

Notes

[1] In addition to the cited references, other prominent mentions of the neuroscience and education argument include:

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[2] Despite this demonstrated success, parents and teachers recently asked Case why one should bother teaching number sense. Wouldn't it be more effective and beneficial, they suggested, to exploit the Mozart effect? These parents and teachers had read about the contributions of brain science to education. (See Begley, 1996; Jones, 1995.) The Mozart effect is the claim that when children exercise cortical neurons by listening to classical music (unfortunately not R&B or heavy metal), they are also strengthening brain circuits used for mathematics. So the neuroscience and education articles do have an audience and do have repercussions for instruction and research.

[3] The author thanks the editors and reviewers of *Educational Researcher* for their many constructive comments and criticisms on earlier versions of this article.

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