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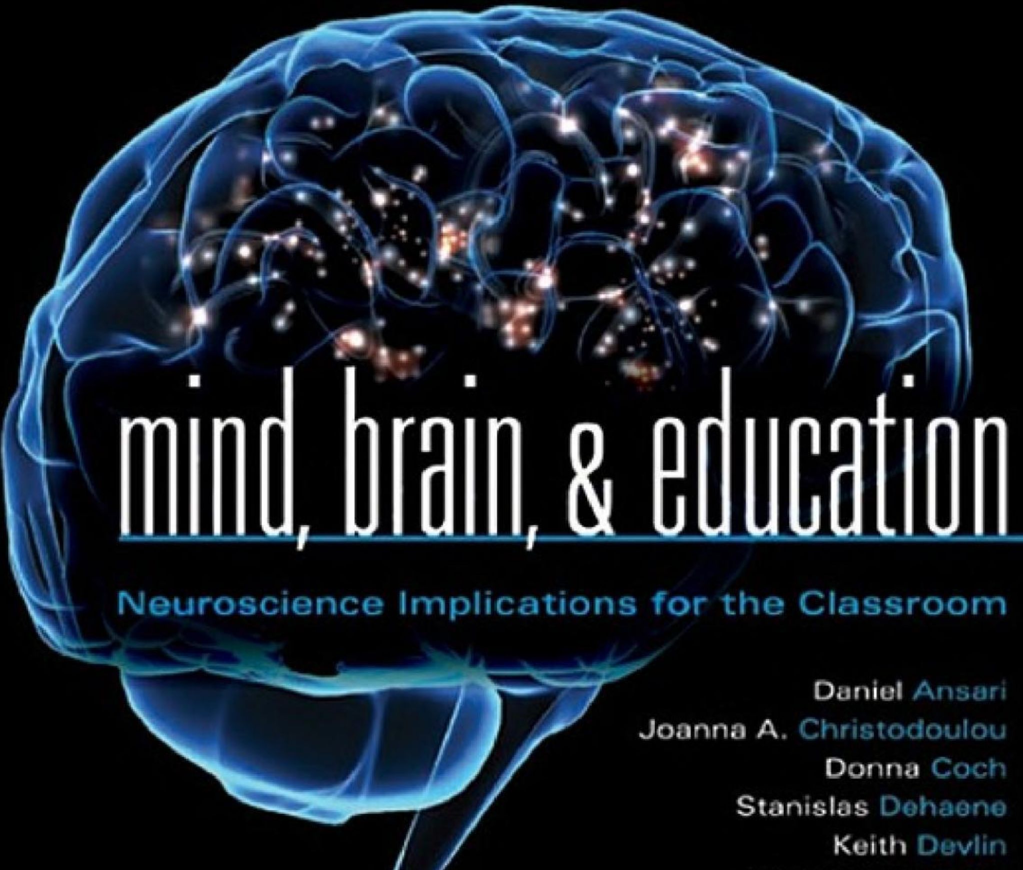
EDITOR



mind, brain, & education

Neuroscience Implications for the Classroom

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About the Editor

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David A. Sousa, EdD, is an international consultant in educational neuroscience and author of a dozen books that suggest ways that educators and parents can translate current brain research into strategies for improving learning. A member of the Cognitive Neuroscience Society, he has conducted workshops in hundreds of school districts on brain research, instructional skills, and science education at the preK–12 and university levels. He has made presentations to more than 100,000 educators at national conventions of educational organizations and to regional and local school districts across the U.S., Canada, Europe, Australia, New Zealand, and Asia.

Dr. Sousa has a bachelor's degree in chemistry from Massachusetts State College at Bridgewater, a Master of Arts in Teaching degree in science from Harvard University, and a doctorate from Rutgers

University. His teaching experience covers all levels. He has taught senior high school science and served as a K–12 director of science, a supervisor of instruction, and a district superintendent in New Jersey schools. He has been an adjunct professor of education at Seton Hall University and a visiting lecturer at Rutgers University.

Prior to his career in New Jersey, Dr. Sousa taught at the American School of Paris and served for five years as a Foreign Service Officer and science advisor at the USA diplomatic missions in Geneva and Vienna.

Dr. Sousa has edited science books and published dozens of articles in leading journals on staff development, science education, and educational research. His popular books for educators include: *How the Brain Learns*, third edition; *How the Special Needs Brain Learns*, second edition; *How the Gifted Brain Learns; How the Brain Learns to Read; How the Brain Influences Behavior;* and *How the Brain Learns Mathematics*, which was selected by the Independent Publishers Association as one of the best professional development books of 2008. *The Leadership Brain* suggests ways for educators to lead today's schools more effectively. His books have been published in French, Spanish, Chinese, Arabic, and several other languages.

Dr. Sousa is past president of the National Staff Development Council. He has received numerous awards from professional associations, school districts, and educational foundations for his commitment to research, staff development, and science education. He recently received the Distinguished Alumni Award and an honorary doctorate from Massachusetts State College (Bridgewater), and an honorary doctorate from Gratz College in Philadelphia.

Dr. Sousa has been interviewed by Matt Lauer on the NBC *TODAY* show and by National Public Radio about his work with schools using brain research. He makes his home in south Florida.

Introduction

David A. Sousa

You hold in your hands a historical publication. This book is the first to bring together some of the most influential scholars responsible for giving birth to a new body of knowledge: *educational neuroscience*. This newborn's gestation period was not easy. Lasting for several decades, it was difficult and often contentious. Identifying the parents was elusive at best, as more than a few prominent candidates denied kinship. Just naming the offspring was a daunting challenge and more exhausting than herding cats. Nevertheless, the birth occurred recently with the help of the visionaries who have contributed to this book. And teaching will never be the same again.

For centuries, the practice of medicine was an art form, driven by creativity and hope, but with little understanding of how to cure disease. Physicians tried certain treatments and administered specific herbs or potions based largely on their previous experiences or on advice from colleagues. They did not know why some treatments worked on one individual and not another, or why they worked at all. Their practice was essentially trial and error, with an occasional stroke of luck. All that changed when Alexander Fleming discovered penicillin in 1928. Although it took more than a decade for penicillin to be mass produced, it gave physicians their first drug for fighting several serious diseases. Furthermore, by understanding how penicillin disrupted the reproduction of bacteria, physicians could make informed decisions about treatment. Medical practice was not just an art form, but had also crossed the threshold into the realm of a science.

The birth of educational neuroscience occurred with the help of the visionaries who have contributed to this book. And teaching will never be the same again.

Today, a similar story can also apply to teaching. Teachers have taught for centuries without knowing much, if anything, about how the brain works. That was mainly because there was little scientific understanding or credible evidence about the biology of the brain. Teaching, like early medicine, was essentially an art form. Now, thanks to the development of imaging techniques that look at the living brain at work, we have a better understanding of its mechanisms and networks. Sure, the brain remains an enormously complex wonder that still guards many secrets. But we are slowly pulling back the veil and gaining insights that have implications for teaching and learning.

Since the 1990s, educators all over the world have come to recognize that there is a rapidly increasing knowledge base about the human brain. Through numerous articles, books, videos, and other presentations, they have also become aware that some of this knowledge could inform educational practice. What many educators may not realize, however, is that researchers and practicing educators have worked diligently to establish a legitimate scientific area of study that overlaps psychology, neuroscience, and pedagogy. The result is educational neuroscience (see fig. I.1).

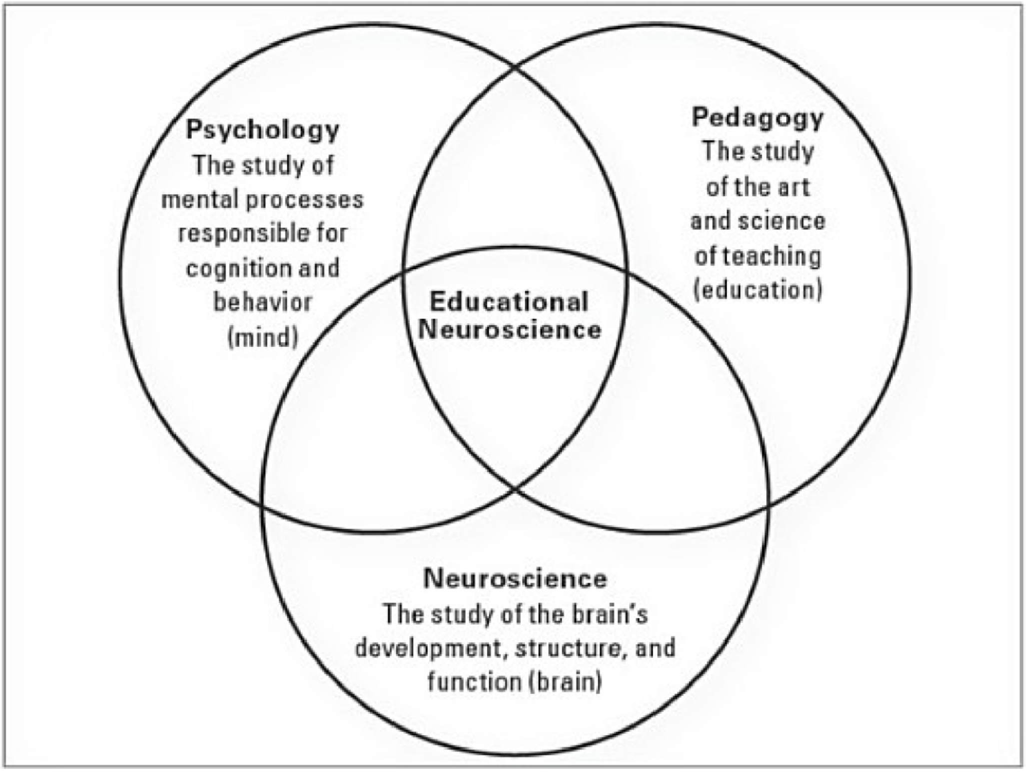

Figure I.1: The emergence of educational neuroscience at the intersection of psychology, neuroscience, and pedagogy.

Until recently, teaching, like early medicine, was essentially an art form.

As exciting as all this seems, understandable skepticism and numerous questions still exist. What specific research applies to pedagogy? Will it benefit students? How do we know the research is being interpreted accurately? Can it be reasonably adapted to our schools and classrooms?

The emergence of a new body of knowledge should be cause for celebration and, in this case, especially among educators. Here in these pages you will discover why we are celebrating. Some of the major pioneers in educational neuroscience explain recent discoveries about the human brain and discuss the influence these discoveries can have on teaching and learning—some now, some in the near future.

The contributors will explore questions such as these:

- How and when did educators get involved with neuroscience?
- How does neuroimaging contribute to our understanding of how the brain learns?
- In what ways is neuroscience research already having an impact on teaching and learning?
- In what ways do emotions affect our ability to learn?
- How does a child acquire spoken language?
- What brain networks are required to learn how to read?
- If we are born with an innate number sense, how can teachers use this to help students learn arithmetic and mathematics more successfully?
- How does the brain represent quantity and numbers?
- What is creativity, and can it be taught?
- In what ways do the arts contribute to brain development?
- What does the future hold for educational neuroscience?

Writing about all the areas researchers are currently investigating that could have an impact on educational neuroscience would fill a volume ten times the size of this one. So it became necessary to focus on those areas that have the greatest potential for affecting educational practice now or in the near future.

We begin with some background on how this new area of study evolved over the past few decades. In chapter 1, I discuss how and why I and a few other educators got so involved following the explosion of brain research in the

1980s and 1990s. Our entry into this new area of study generated considerable controversy, but our tenacity paid off.

The main reason for that explosion was the development of imaging technology that allowed researchers to peek inside the workings of the living brain. Michael Posner was one of the pioneers in using the new imaging devices, and he explains their contribution to neuroscientific research in chapter 2.

Some of the research findings from neuroscience are already being used in educational practice. In chapter 3, Judy Willis, a medical doctor turned classroom teacher, writes about those areas that are already having an impact on instruction and offers numerous suggestions for teachers to consider.

Students do not just develop intellectually in schools, but also socially and emotionally. Despite our understanding that emotions have an impact on learning, some teachers are still unsure how to incorporate emotions into their lessons. Mary Helen Immordino-Yang and Matthias Faeth cite five major contributions in chapter 4 that neuroscience has made to the research on how emotions affect learning, and they suggest three strategies that have proven effective.

Speaking and learning to read are among the early skills that young children learn. In chapter 5, Diane Williams explains what neuroscience research has revealed about the cerebral networks involved in learning spoken language. She debunks popular myths about learning language and discusses some major implications that this research has for teaching and learning.

Because reading is one of the most challenging tasks the young brain will undertake, it has gained a lot of attention from neuroscientists and cognitive psychologists. Consequently, we have devoted two chapters to this topic. In chapter 6, John Gabrieli and his colleagues review the major research findings and current understandings about how a child's brain learns to read, what is different in the brain of a child who struggles to read, and how the neuroscience of reading may come to play an important role in education. Donna Coch in chapter 7 also discusses the complex processes involved as the young brain learns to read, but focuses more on the role of the visual and auditory processing systems as well as the development of the alphabetic principle, semantics, and comprehension.

Another area of great interest to neuroscience researchers is how the brain represents quantity and how it engages neural networks to learn to carry out arithmetic and mathematical computations. Three renowned researchers in this area offer insights for educators. Keith Devlin suggests in chapter 8 that the brain's strength as a pattern-seeker accounts for many of the difficulties people have with basic arithmetic operations. He offers some proposals to educators on instructional approaches in mathematics based on the recent neuroscience research. In chapter 9, Stanislas Dehaene explains how neuroimaging has helped us to understand the three networks our brain uses to evaluate the number of a set of objects and suggests ways this and other discoveries can be used to help students learn arithmetic and mathematics. Not all brains do well with mathematics, however; in chapter 10, Daniel Ansari reviews what is currently known about how the brain computes. He discusses how the brains of individuals with and without mathematical difficulties differ both functionally and structurally. In addition, he suggests ways in which research findings may inform both the thinking and practice of educators.

What is creativity, and can it be taught? How do the arts help students develop competency in other subject areas? These questions are of particular importance because in too many school districts, arts are still thought of as frill subjects and are thus easy targets when budgets get tight. In chapter 11, Mariale Hardiman addresses these important questions and offers suggestions that teachers can use to incorporate the arts in all subjects and at all grade levels.

Because many of the authors refer to specific regions of the brain in their discussion, we have included two diagrams (figs. I.2 and I.3, pages 6–7) that should help readers locate these regions. In addition, we have included a glossary at the end of the book (pages 271–274) that defines the less-familiar scientific terms used by the authors.

With all these promising research findings, where do we go from here? To answer that question, in chapter 12, Kurt Fischer and Katie Heikkinen suggest that new ways of thinking about teaching will need to emerge if educational neuroscience is to meet its promise in the future.

Exploring these chapters will give the reader a sense of where this new field of educational neuroscience is now, and where it is headed. These authors have been instrumental in supporting this emerging area of study. Their ideas and continuing research are sure to help educators find applications to their practice that will benefit all students.

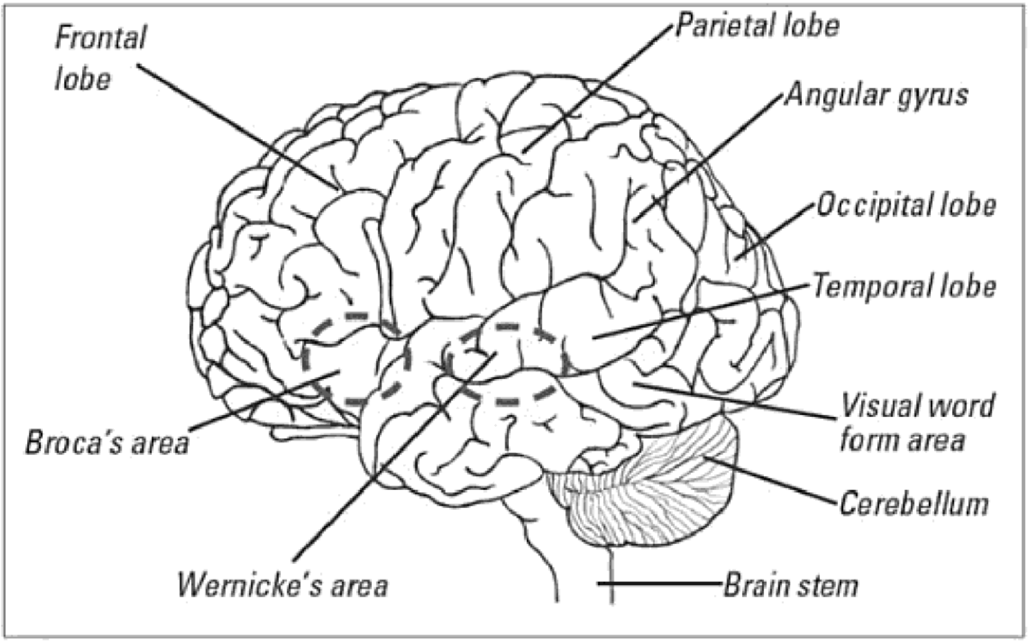

Figure I.2: The exterior regions of the human brain referred to in this book.

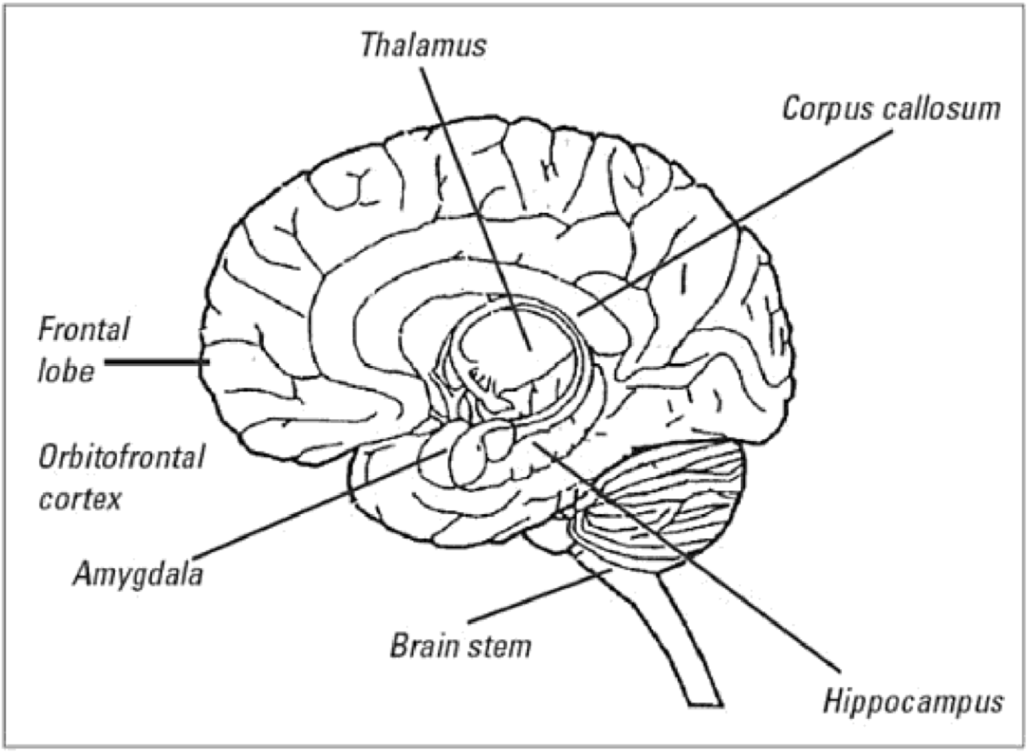

Figure I.3: A cross-section of the human brain showing the major regions referred to in this book.

David A. Sousa

David A. Sousa, EdD, is an international consultant in educational neuroscience and author of a dozen books that suggest ways of translating brain research into strategies for improving learning. He has presented to more than 100,000 educators across the U.S., Canada, Europe, Australia, New Zealand, and Asia. In New Jersey, he taught high school chemistry and served in administrative positions, including superintendent of schools. He was an adjunct professor of education at Seton Hall University and a visiting lecturer at Rutgers University.

Dr. Sousa has edited science books and published dozens of articles in leading journals on staff development, science education, and educational research. His books have been published in French, Spanish, Chinese, Arabic, and several other languages. He is past president of the National Staff Development Council. He has received honorary degrees and numerous awards from professional associations, school districts, and educational foundations for his commitment to research, staff development, and science education.

In this chapter, Dr. Sousa reviews the history of how some educators became deeply interested in the emerging research on the brain and began to look for applications in schools and classrooms. Despite criticism from some researchers that any such applications were premature, a cadre of determined educators sought to collaborate with neuroscientists—a dialogue that continues to grow to this day.

Chapter 1

How Science Met Pedagogy

David A. Sousa

No one can say exactly when the area of study now known as educational neuroscience was born. Rather, the domain emerged slowly after at least four decades of research on the brain and amid heated battles between well-intentioned parties who held drastically different views about the application of neuroscientific discoveries to educational practice. To understand why these conflicting views developed, it is helpful to review how advances in brain research and imaging technology forever changed cognitive psychology and neuroscience.

Scientific Developments

Psychologists, of course, have been studying the brain for over a century. Behavioral psychologists made inferences about brain function by watching how people responded to certain stimuli (remember Pavlov and his dogs?). Cognitive psychologists drew conclusions about brain growth and development by watching how and when children acquired certain skills. Neurologists had to infer brain function by looking at case studies in which a patient's behavior changed as a result of some sort of brain trauma, such as stroke, lesion, or hemorrhage. But those studying the brain at that time had to face one inescapable fact: the only way they could actually look at a human brain was in an autopsy. In an autopsy, one can learn about the location and size of various brain structures, but nothing about their true function. Even neurologists had to wait until an autopsy was performed to confirm which area of the brain had sustained damage. Conventional X-rays were no help because they revealed only hard tissue, such as bones and teeth, and they damaged healthy brain cells.

In the early 1970s, a new technology was developed independently by

Godfrey Hounsfield at the EMI Laboratories in London and Allan Cormack at Tufts University in Massachusetts. Called computerized axial tomography, or CAT or CT scan, this instrument manipulated low-power X-rays to detect variations in soft body tissues. Here, at last, was a device that revealed structures in the living human brain. Hounsfield and Cormack shared the 1979 Nobel Prize in Medicine for their discovery. A few years later, another technology for looking at body tissue, called magnetic resonance imaging, or MRI, was developed by Paul Lauterbur at Stony Brook University in New York and enhanced by Peter Mansfield at the University of Nottingham in the United Kingdom. The Nobel Prize in Medicine was awarded to Lauterbur and Mansfield in 2003 for their discoveries that led to MRI.

CAT and MRI scans were remarkable tools for medical diagnosis of brain trauma. But these devices showed brain *structure*. Neuroscientists needed a technology that could look at brain *function*. The first of these was positron emission tomography, or PET scans, developed in the late 1970s as a result of the work of Michel Ter-Pogossian, Michael Phelps, and others at the Washington University School of Medicine in St. Louis. PET scans revealed which parts of the brain were more or less active at any given moment. However, they were not practical for looking at the brains of otherwise normal individuals because they required the injection of a radioactive substance. A noninvasive technology, called functional magnetic resonance imaging, or fMRI, was developed in the early 1990s by Seiji Ogawa about the same time that U.S. President George H. W. Bush declared the 1990s the "Decade of the Brain." A massive infusion of federal research dollars and advances in imaging technology resulted in an explosion in the number of studies in the neurosciences.

From that time forward, findings from brain research regularly flooded the professional journals and popular media. Almost weekly a major news story appeared regarding research on the brain. It was only a matter of time before educators began to explore whether any of this research would have an effect on what they did in schools and classrooms. Little did they realize what a hornet's nest they would stir up.

Educators Wade Into the Fray

Every educator and consultant who spread the word about the findings of brain research has a story to tell. My own story revolves around my love for science and my passion for teaching. Seeing these two important areas beginning to merge was an exhilarating experience that set the stage for major changes in my life and career. Because I was fortunate to be there at the beginning, describing my experiences also reveals much about how the domain of educational neuroscience evolved and the barriers that had to be overcome.

Professional Development in the 1980s

In the early 1980s, I was working in a fine New Jersey school district as the K–12 supervisor of science. A new superintendent arrived and asked me to remake the district's staff development program into a cutting-edge experience with a long-term focus on positively affecting teacher growth and student achievement. I had other new duties as well, but upgrading the professional development program was my main task.

I started going to national education conferences to get a sense of which cutting-edge issues could form the framework of an effective and long-range professional development program. The learning styles movement was already underway. It was an offshoot of research by Roger Sperry in the 1960s (and later by Michael Gazzaniga), who worked with so-called split-brain patients. These were patients with severe epilepsy whose treatment involved severing the nerve fibers connecting the two cerebral hemispheres. As the patients recovered, Sperry observed that each hemisphere of these split brains had distinctly different functions that were not readily interchangeable (Sperry, 1966). Sperry won the 1981 Nobel Prize in Medicine for this work.

In the late 1970s and 1980s, the notion that various regions of the brain performed different functions formed the basis for explaining why students seem to have different learning styles. Educational researchers Rita and Ken Dunn of St. John's University developed a model that identified about twenty components of learning styles (Dunn & Dunn, 1978). Other models, such as Bernice McCarthy's 4MAT and Susan Kovalik's integrated thematic instruction, also claimed to be tied to brain research. Although these models had little research support from cognitive psychology, they were very attractive to educators because teachers' own experiences suggested that students learn in various ways.

One of the most popular speakers at that time was Madeline Hunter. She had served as a psychologist at Children's Hospital and Juvenile Hall in Los Angeles. She wanted to work full-time with typical children, however, and soon became a professor at the University of California, Los Angeles and principal of the UCLA lab school. At national conferences she often remarked on how surprised she was that teachers were working hard in the classroom but were not using instructional strategies based on recent research in behavioral and cognitive psychology.

As a former chemistry teacher and science educator, I found Hunter's message exciting because she was advocating the linking of my two loves—science and teaching. In 1985, I had an opportunity to talk with her privately for a few minutes after her keynote speech at an education conference. She suggested that I research the findings from cognitive psychology and neuroscience and share this with the district's teachers as part of our professional development program. She was convinced that once teachers understood the research, they could find ways to translate it into educational practice. Furthermore, she believed that we would continue to unlock the mysteries of the human brain and how it processes and learns. Now we can enable teachers to use that knowledge to accelerate the learning process. Her favorite expression was that "teaching is no longer a 'laying on of hands.' " Instead, she said, it was becoming a profession that combines science with art to create a better, more productive classroom in which all children learn (Hunter, 1982).

Hunter had her critics, but her work greatly influenced the nature of professional development programs for teachers all over the world. Today, numerous state and federal programs require that professional development in school districts be based on scientific research. Of course, Hunter's belief that science would discover more about how the brain works was dramatically bolstered by the development of the brain-imaging technologies that I discussed earlier.

Increased Awareness About the Brain

Hunter was not the only important voice urging educators to look at the connections between science and pedagogy. Researchers Michael Posner and Michael Gazzaniga were working as early as the 1970s toward integrating neuroscience and psychology. In 1983, Leslie Hart published *Human Brain and Human Learning*. In this seminal work, Hart argued that teaching without an awareness of how the brain learns is like designing a glove with no sense of what a hand looks like. If classrooms are to be places of learning, Hart continued, then the brain—the organ of learning—must be understood and accommodated (Hart, 1983).

The same year, Howard Gardner (1983) of Harvard University published *Frames of Mind: The Theory of Multiple Intelligences*. He suggested that humans possess at least seven different intelligences (now up to nine) in varying degrees. Robert Sternberg (1985) at Yale proposed a triarchic theory of intelligence that distinguished three types of intelligence. Although not directly connected to neuroscience, Gardner's and Sternberg's theories shook some fundamental beliefs about intelligence. They suggested that people can be smart in many different ways and thus upset the long-held notion of intelligence as a singular construct. Furthermore, they caused educators (and parents) to refocus their attention on the workings of the brain and to ask whether this new information should be getting to classroom teachers.

Along with other educators, I began recognizing during the late 1980s that some of the findings from brain research could have definite implications for educational practice, which would require updating teachers about these new discoveries—no small task. Whenever I asked teachers and administrators to tell me what they knew about how the brain actually learned, I almost always heard references to Ivan Pavlov, Jean Piaget, and John Dewey, and some ideas about time on task and repetition. If I asked them to tell me two or three new things they had recently learned about the brain, there was usually an awkward silence. We had our work cut out for us.

In 1994, after serving for several years as superintendent of schools in New Jersey, I felt it was time to move onto the national scene and join the growing cadre of respected educators who were spreading the word about the potential benefits to education of research in the neurosciences. This cadre included, among others, Geoffrey and Renate Caine, Eric Jensen, Robert Sylwester, and Patricia Wolfe.

One of the more perplexing issues facing our cadre was selecting a short title to describe what we were advocating. Our mission was to encourage teachers to use instructional strategies in their classrooms that were consistent with research in brain-related sciences. "Brain-based education" was one of the earlier labels. It seemed attractive at first, but then I thought, "Isn't all learning brain based? What's the alternative?" Others preferred "brain-compatible" and "brain-friendly." I finally settled on "translating brain research into classroom practice." And off I went to spread the word.

What Was Brain Research Revealing?

Much of what was being revealed in the 1990s about the brain had little to do with teaching and learning. Most of the studies focused on understanding brain trauma, disease, and developmental problems. But within this expanding sea of information, one discovered little islands where the research findings could have an impact on pedagogy. Many more discoveries have been made since then, but the following are some of the major ones of that time:

- **Movement enhances learning and memory.** The typical classroom setting in which students "sit and get" was challenged by research findings showing that the brain is more active when learners are moving around. Movement brings additional fuel-carrying blood to the brain. It also allows the brain to access more long-term memory areas (an ancient survival strategy), thereby helping students make greater connections between new and prior learning (Scholey, Moss, Neave, & Wesnes, 1999). Furthermore, exercise was shown to be strongly correlated with increases in brain mass and cell production, as well as in improved cognitive processing and mood regulation. These findings should encourage teachers to get students up and moving in their classrooms. It also should discourage administrators from eliminating recess and physical education classes, a common practice in the current era of high-stakes testing.

- **Emotions have a great impact on learning.** Teachers of the elementary grades are accustomed to dealing with their students' displays of emotion. In contrast, teachers at the secondary level are trained to deliver content—and lots of it! They have little time to deal with their students' emotional development and often assume that students should simply "act like adults." Daniel Goleman's book *Emotional Intelligence* described the influence and power of emotions and how important it is for individuals to learn at an early age the connections between their feelings and their actions (Goleman, 1995). The immense popularity of Goleman's book prompted educators to look at the impact of emotions in the classroom, especially in secondary schools. Teachers need to understand the biology of emotions, especially stress, and to recognize that students cannot focus on the curriculum unless they feel physically safe (for example, from weapons or violence) and emotionally secure (they perceive that teachers respect them and care about their success).

- **The varying pace of brain development explains the behavior of children and adolescents.** Teachers and parents are well aware of the unpredictable, often risky behavior of preteens and adolescents. Emotional outbursts and physical aggression are common ways for these youngsters to deal with situations. We often blame these behaviors on changing hormones. A landmark longitudinal study of brain growth using imaging technology revealed that the emotional areas of the brain are fully developed by about age ten to twelve, but the regions responsible for rational thought and emotional control mature closer to age twenty-two to twenty-four (Giedd et al., 1999). This finding does not excuse child and adolescent misbehavior, but it explains it and suggests that there are more appropriate, effective interventions than saying, “You should have known better.”

- **The school’s social and cultural climates affect learning.** Schools tend to be so focused on academics and testing that they often are unaware of the powerful effect that social and cultural forces have on students. Humans are social beings, and students are constantly interacting with their peers and teachers. To what degree do students feel welcomed and respected by their peers and teachers? How much will they succumb to peer pressure? What risks are they willing to take to feel socially accepted? Imaging studies have revealed brain regions that appraise the meaning of an event and decide what emotional response to use in a social context (Heatherton et al., 2006; Zahn et al., 2007). These and other findings have spawned a new field of study called social cognitive neuroscience. This area of inquiry combines social psychology with cognitive neuroscience and aims to describe behavior using data from brain imaging and similar technology. School culture is characterized in part by openness of communication, level of expectations, amount of recognition and appreciation for effort, involvement in decision making, and degree of caring. All of these affect an individual’s self-esteem. Educators need to pay much more attention to strengthening the positive aspects of the school’s social and cultural climates. Regrettably, we have seen the kinds of violent acts that students can commit when they feel disaffected from their school.

- **The brain can grow new neurons.** For a long time scientists were convinced that neurons were the only body cells that did not regenerate. The number of neurons an individual had was always declining. But in the late 1990s, researchers found that the brain does indeed grow new neurons, at least in a part of the brain called the hippocampus, an area responsible for encoding long-term memories (Kempermann & Gage, 1999). Later research indicated that this regrowth, called neurogenesis, was highly correlated with mood, memory, and learning. Moreover, it could be enhanced by good nutrition and regular exercise as well as by maintaining low levels of stress (Kempermann, Wiskott, & Gage, 2004).

By knowing this, teachers can help students understand how their brain grows and can explain the kinds of behaviors that lead to consistent neural growth and brain health.

- **The brain can rewire itself.** Previous notions about neural networks held that they changed very slowly and even slower as we passed middle age. Early in the 2000s, new research evidence showed that the brain could rewire itself (a process called neuroplasticity) as a result of environmental input, and at a faster pace than originally thought. This finding led researchers to examine the brain scans of young struggling readers (many diagnosed with dyslexia) and eventually to devise computer programs and protocols that actually rewired these students' cerebral networks to perform more like those of good readers (Shaywitz, 2003; Simos et al., 2002). What an amazing discovery and application to pedagogy (Sousa, 2005)! Furthermore, the good news for adults is that neuroplasticity continues throughout our lifetime.
- **Short-term memory is not so temporary.** Ask teachers anywhere in the world how long they want their students to remember what they taught them, and the answer is always the same: "Forever!" Yet they all know this is just not reality. Why do students forget so much of what they are taught, especially in high school? As a result of extensive research on memory systems, two findings in particular helped shed light on this question (Squire & Kandel, 1999). First, short-term memory seems to consist of two components: a brain area that initially processes incoming information for just a few seconds, referred to now as immediate memory, and another area where information is consciously processed for extended periods, called working memory. Conventional wisdom used to be that working memory held items from a few minutes up to a day or so before it faded from the system. But it seems that a student actually can carry items for up to several weeks in working memory and then discard them when they serve no further purpose—in other words, after the student takes the test. That explains why students often fail to recall topics that the teacher taught a few months earlier.

  Second, in the typical classroom, sense and meaning appeared to be among the major criteria that the brain uses in deciding what to encode to long-term memory. Teachers work hard at having their presentations make sense, but they do not always do enough to make the learning meaningful or relevant. These two findings suggest the need to focus on strategies that enhance retention of learning and on curricula that students perceive as relevant to their lives (Sousa, 2006).

- **Sleep is important for memory.** Parents always tell their children how important it is to get enough sleep. This advice usually is based on the need to give the body, including the brain, sufficient rest so that one can wake up refreshed and tackle the activities of the new day. Researchers found that the brain is incredibly active during sleep, carrying out processes that help the brain to learn, make connections, remember, and clear out clutter (Schacter, 1996). A brain that is sleep deprived has trouble capturing all sorts of memories. Studies showed that sleep-deprived students were more likely to get poorer grades than students who slept longer and also more likely to get depressed (Wolfson & Carskadon, 1998). Many secondary students (and their teachers) come to school sleep deprived because their average sleep time is only five to six hours. By knowing about sleep research, teachers can emphasize to students the importance of getting adequate sleep; most teenagers need about nine hours. With sufficient sleep, students have a better chance of remembering all the good information and skills they learn in school that day.

For centuries, effective teachers discovered through experience what strategies to use and how to implement them. But they did not know why the strategies worked, or did not work, on different occasions. That is what the findings from these studies in cognitive neuroscience were providing—the *why*. When teachers know the why, they can be much more masterful in applying instructional strategies.

We Begin to Spread the Word

Neuroscientists in the 1990s were working hard at finding new evidence of how the brain works, but they were not thinking much about applications to pedagogy. One neuroscientist said to me, “My job is to discover the inner workings of the brain. I haven’t a clue as to whether my findings have any applications to teaching. You’re the educator, so that’s your job.” And that is exactly what I and other educators who were intently following the brain research did. We looked for potential applications to pedagogy, wrote about them, and traveled internationally to tell other educators about them.

Neuroscientists in the 1990s were working hard at finding new evidence of how the brain works, but they were not thinking much about applications to pedagogy.

During the 1990s, just about every regional and national education conference had one or more workshop sessions on brain research. I presented a number of these workshops and found most educators to be very interested in the information. Meanwhile, individual school districts in the United States, Canada, and other countries were exposing their professional staff to the implications of brain research on pedagogy. Articles on the subject began appearing in professional journals. Ron Brandt, editor of *Educational Leadership*, the widely read journal of the Association for Supervision and Curriculum Development (ASCD), saw the emerging research as a significant development and encouraged contributions on this subject. Books by educators linking brain science to pedagogy flooded the market. All of this activity attracted the attention of psychologists, and it did not take them long to make their views known.

The Critics Pounce

Some psychologists admitted that there were potential applications of neuroscience to pedagogy but advised caution. Still others insisted that teachers did not think scientifically and thus were not qualified to judge the applications of neuroscientific research. They criticized educators for not reflecting on their daily practice and not documenting their own successful (and unsuccessful) instructional strategies. The psychologists' argument was that although educators could potentially make significant contributions to understanding of the brain, most failed to apply the scientific method and did not know how to do reliable research in their own classrooms. Consequently, much of the information gathered in education was anecdotal, poorly documented at best, and of little value to the profession. Cognitive psychologists felt that they should be the ones assessing which research findings have applications to pedagogy and that they alone should be the bridge between neuroscientists and educators.

One of the most vocal critics was John Bruer. In the late 1990s, he wrote several articles criticizing the linking of brain research to education. He said educators should resist trying to understand brain research, implying that they weren't smart enough. Instead, he suggested, they should look to cognitive psychology for research guidance and applications. In one article he jibed that if brain-based education were true, then "the pyramids were built by aliens—to house Elvis" (Bruer, 1999, p. 656). Furthermore, he insisted that it would take twenty-five years before there would be any practical applications of brain research to the classroom. Fortunately, Bruer's prediction was way off. By

2006, he took a more moderate stand, saying that focusing solely on neuroscience gives insufficient attention to cognitive psychology (Bruer, 2006). Nevertheless, many of his criticisms have been overtaken by the impressive amount of brain research continuing to emerge. Ironically, two of the researchers that Bruer often cites in his articles, Michael Posner and Stanislaus Dehaene, support a strong relationship between neuroscience and education and are contributors to this book.

Any field of serious study, especially an emerging one such as educational neuroscience, should be monitored by qualified skeptics. Healthy skepticism has often advanced scientific thought. However, some of the skeptics intentionally selected marginal issues to criticize the myths that they claimed educators and consultants were perpetuating. Gender differences, left-right hemisphere specialization, and sensitive developmental periods were topics that psychologists chose most frequently as examples, calling them "neuromyths." They argued that nothing from the research in these areas would have any practical application to pedagogy.

Anyone taking that stand even ten years ago was not keeping up with the research. Neuroscientists did not dispute that there are definite differences in the structure and function of male and female brains. Nor did anyone dispute that areas of the cerebral hemispheres have specialized functions in most people. And there already was ample evidence that there are sensitive as well as critical periods during the development of the young brain when neural networks are growing and consolidating. The question was the degree to which these factors affected learning in children.

In the critics' defense, it is true that some less-informed consultants were stretching the applications of these research findings beyond what was appropriate. Statements such as "Girls aren't that good at math" or "He's too left-brained to be creative" did not serve our cause and lent further ammunition to the critics. Add to this the unfortunate "Mozart effect" misunderstandings (Rauscher, Shaw, & Ky, 1993) and the "water bottle on every desk" mantra, and it was no surprise that even those of us who were trying to define legitimate research applications were under fire. Nonetheless, some neuroscientists, cognitive psychologists, and educators were slowly recognizing that there was a common ground within their three respective fields where they could meet and seriously discuss the present and future effects that discoveries in neuroscience might have on pedagogy.

> Despite the critics, some neuroscientists, cognitive psychologists, and educators were

slowly recognizing that there was a common ground within their three respective fields.

The Dust Settles

With the advent of the 21st century, the tide turned and the battles subsided, especially when prestigious universities established programs and institutes around the link between neuroscience and education. Some of the schools sponsoring these programs included Cornell University, Dartmouth College, Harvard University, University of Southern California, University of Texas at Arlington, and University of Washington. Various professional associations also had become involved. They include the American Educational Research Association Special Interest Group on the Brain and Learning, the Dana Foundation, the International Mind, Brain, and Education Society, the Organisation for Economic Co-operation and Development, and the Society for Neuroscience. One major contribution to these efforts came from the U.S. National Research Council, which published a book called *How People Learn* (Bransford, Brown, & Cocking, 2003).

Interest in the applications of neuroscience to pedagogy also was rapidly developing in other countries. Institutes and study groups were forming in Australia, Canada, Japan, France, India, Italy, Mexico, the Netherlands, and the United Kingdom, among others. Several international conferences, such as Learning Brain Europe, are now held regularly around the world, centered on areas of brain research that have an impact on teaching and learning.

One recent study that helped shed light on possible areas of agreement was prompted by the work of Tracey Tokuhama-Espinosa, a doctoral candidate whose thesis focused on the development of standards in the new field that she referred to as “neuroeducation,” or “mind, brain, and education science.” Her work involved a review and meta-analysis of more than 2,200 related documents, plus asking a panel of twenty recognized leaders in neuroscience, psychology, and education for their views on what should be the standards for this new field, now also referred to as educational neuroscience (Tokuhama-Espinosa, 2008).

The result was a compilation of several dozen beliefs about the brain and learning that were filtered through the panel, which classified them as to whether they were well established, probably so, intelligent speculation, or popular misconceptions (those “neuromyths” mentioned earlier). Not surprisingly, the panel members’ ratings varied, but there was enough consistency between the panel’s ratings and the findings from the author’s extensive meta-analysis of the literature that she was able to extract twenty-two "principles" that describe how the brain learns (Tokuhama-Espinosa, 2008).

This study and other published articles make clear that there is not yet broad agreement on the standards that define educational neuroscience. Perhaps those who continue to focus on the somewhat contrived and now stale neuromyths will shift their efforts instead to the research findings that have real potential for enhancing educational practice.

We have come a long way since 2000, and the future looks promising. More teachers are now paying attention to this area. Teachers are, after all, the ultimate "brain changers." They are in a profession of changing the human brain every day. So as neuroscientists continue to discover the inner workings of the brain, as cognitive psychologists continue to look for explanations of learning behavior, and as educators continue to apply research to improve their teaching, not only will this new field gain independence, but, most important, also greatly improve the quality and effectiveness of educational experiences for our children.

Teachers are, after all, the ultimate "brain changers." They are in a profession of changing the human brain every day.

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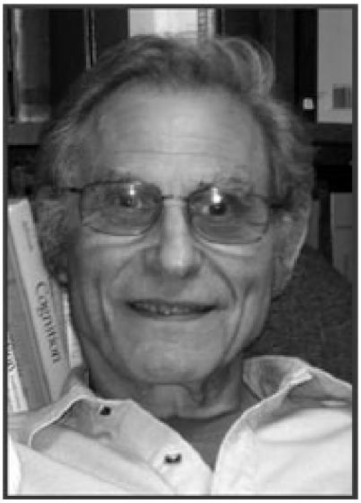
Michael I. Posner



Michael I. Posner, PhD, is Professor Emeritus at the University of Oregon and Adjunct Professor of Psychology in Psychiatry at the Weill Medical College of Cornell University, where he served as founding director of the Sackler Institute. With Marcus Raichle, he developed studies of imaging the human brain during cognitive tasks. He has also worked on the anatomy, circuitry, development, and genetics of three attentional networks underlying maintaining alertness, orienting to sensory events, and voluntary control of thoughts and ideas. His methods for measuring these networks have been applied to a wide range of neurological, psychiatric, and developmental disorders, and to normal development and school performance.

His current research, a longitudinal study of preschool children, is designed to understand the interaction of specific experience and genes in shaping attention and self regulation. His work has been recognized by his election to the National Academy of Sciences, by the 2009 National Medal of Science, by seven honorary degrees, and by the Distinguished Science Award of the American Psychological Association, the Karl Spencer Lashley Award by the American Philosophical Society, and the Mattei Dogan Award from the International Union of Psychological Science, among others.

In this chapter, Dr. Posner explains how advances in neuroimaging technology led to deeper understandings about how the brain works. He also suggests how these understandings may apply to educational practice.

Chapter 2

Neuroimaging Tools and the Evolution of Educational Neuroscience

Michael I. Posner

The key element in the evolution of educational neuroscience was the development of cognitive neuroimaging in the late 1980s. In this chapter, I review the historical record of developments in brain imaging methods such as measurement of changes in blood flow and of electrical and magnetic activity (in both healthy patients and in patients with brain damage). Together, these methods have illuminated the acquisition of literacy, numeracy, expertise, and other aspects of education.

Hemodynamic Imaging

Efforts to image the human brain are ancient, but the modern era began with computerized tomography, or CT scans, which use mathematical algorithms to combine X-rays in such a way as to produce a picture of the brain's structure. However, the images most needed were those showing the brain's *function* during performance of everyday tasks. Efforts to map the function of the brain began by measuring blood flow. Using radionucleides that emit photons when in contact with matter, researchers counted the frequency of emissions to map changes in blood flow at various locations in the brain. The major methods used to develop these maps were single photon emission computed tomography (SPECT) and positron emission tomography (PET) (for an extensive history of this field, see Savoy, 2001).

The images most needed were those showing the brain's *function* during performance of everyday tasks.

Using PET Imaging

In the late 1980s, it became possible to examine changes in the intact brain while people carried out tasks involving thinking. One method used was called positron emission tomography. PET took advantage of the fact that when brain cells are active, they change their own local blood supply. Using PET, it is possible to show which portions of the brain are active. The PET mapping method was first employed to show how, during tasks such as reading or listening to music, much of the brain, but not the whole brain, exhibited increased blood flow (Lassen, Ingvar, & Skinhoj, 1978). In an important early study, researchers compared specific tasks such as navigating from place to place while reading and listening; the results showed clear regional distribution of brain activity—activity that differed depending on the task (Roland & Friberg, 1985). Prior to the development of functional brain imaging, cognitive psychologists had already broken down tasks such as reading, attention, and visual imagery into component operations or subroutines sufficient to program a computer to perform the tasks (Kosslyn, 1980; Posner & Raichle, 1994). Relating these subroutines to specific brain areas was an important step toward making brain maps useful in psychology and education.

An initial step in connecting subroutines to specific brain areas used PET to examine brain activity while participants listened to and read individual words (Petersen et al., 1988). Participants performed a set of hierarchical tasks (shown in table 2.1) that required looking at a fixed point, reading a word out loud, or generating a use for a word. By "subtracting" the imaging results for each subtask, researchers could roughly isolate the mental operations for each step as participants moved up the hierarchy of increasingly complex tasks.

For example, in the simplest situation, researchers compared the brain activity when participants looked at a screen that showed only a fixation point (this was the control state, shown in the first column of table 2.1) with their brain activity when a single visual or auditory noun was presented at intervals of about a second (the stimulation state, the second column). Subtracting the fixation-only condition from the words provided a measure of where seeing or hearing words activated the brain (the third column, in this case, passive word processing). The visual words strongly activated the visual system and the auditory words the auditory system, thus confirming what would be expected.

At the next level, brain activity for the presentation of visual words was subtracted from the activity shown when participants read the same words aloud; thus researchers were able to identify those parts of the brain needed to translate the visual letters into a name and articulate the output. When participants read words aloud, the PET showed major activity in motor areas. At the highest level in table 2.1, participants were asked to generate a use of the presented word: for example, to think of and say a word such as *pound* when presented with the word *hammer*. When they had to produce a use of each noun presented, a brain network was activated that included the left anterior frontal gyrus, the anterior cingulate, parts of the cerebellum, and a posterior temporal-parietal area.

In other words, the highly automated task of reading a word activated one set of areas in the brain, but when subjects had to make a new association with the word, then a different set of areas was activated. During the naming of new associations, it might be concluded, the anterior cingulate was involved in attending to the task, the left frontal area held the input word "in mind," while the posterior area provided the associated meaning. If the same list of words was repeated and participants made the same association, then the strength of the activations decreased. After a few repetitions, producing the association resulted in the same brain activity as simply reading the word aloud (Raichle et al., 1994). Apparently, a few minutes of learning had automated the associations, and they were made more reliably and faster than when they were novel. The brain pathway functioned as though the association was as directly connected to the image of the word as to the process of reading the word. These findings supported the notion that mental operations occur in separate brain areas and showed how quickly these activations could be changed by practice.

Using Functional Magnetic Resonance Imaging (fMRI)

A major development in 1990 was the use of magnetic resonance (MR) to measure localized changes in blood oxygen. PET had required the use of radioactivity to detect blood flow, while MR used no radioactivity—only a high magnetic field—and thus could noninvasively map brain activity (Ogawa et al., 1990). This technology (fMRI) not only was able to reveal much more localized activity than PET, but also had two other features that were very important for cognitive and educational work. First, since fMRI did not use any radioactivity, it could be used with children and to map differences in one individual's brain activity by scanning repetitively. Second, because an individual could be scanned repeatedly without harm, fMRI allowed researchers to combine trials of different types (for example, naming words and generating their uses) within the same series of trials so that participants could not develop a special strategy for each task. Later, the experimenter could average all the word-naming trials separately from the use-generating trials and make the subtraction needed to reveal the networks of brain areas used to generate a simple association.

A major 1990 development was the fMRI that used no radioactivity, was noninvasive, and could be used with children.

Much subsequent work has confirmed and elaborated the meaning of brain-area activations, particularly with respect to reading. For example, in a skilled reader, two important posterior brain areas operate automatically: the left fusiform gyrus and the left temporal parietal lobe (see fig. 2.1). The first of these two areas appears to be involved in chunking visual letters into a unit. Often called the *visual word form area* (McCandliss, Cohen, & Dehaene, 2003), it appears to be of special importance in languages that are irregular in pronunciation. English is a particularly irregular language. For example, the "-ave" in *wave* and *have* are pronounced quite differently. While there has been dispute about this area of the brain (Price & Devlin, 2003), most studies have found that it responds to any group of letters that can be pronounced (for example, *iske* is not a word but can be pronounced using the rules of English and would activate the word form area). The second area, the left temporal parietal lobe, is closer to the auditory system and appears to represent the sound of the word. These two areas operate automatically in skilled readers but did not seem to work well in children having difficulty in learning to read (Shaywitz, 2003).

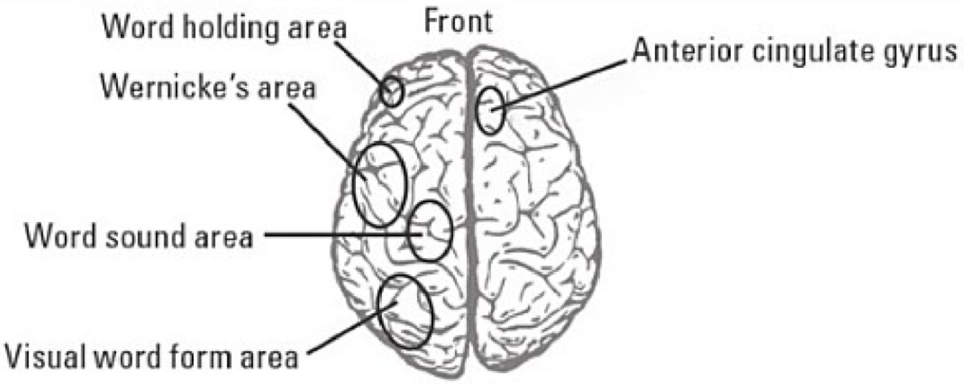


Figure 2.1: Brain areas involved in reading.

These two posterior areas operate in coordination with areas involved in (1) giving effort or attention to the printed word and (2) understanding sentences and longer passages. The anterior cingulate gyrus is a major structure in the executive attention system and is important for regulating other brain networks, including those involved in reading. It operates in conjunction with a left lateral frontal area to hold words in mind while lexical meanings are retrieved from Wernicke's area and from the other highly distributed areas that deal with meaning. Understanding the connotation of a word may also involve information stored in sensory and motor areas.

Use of fMRI has allowed the study of many brain networks not only related to cognitive processes, such as reading, listening, imaging, and so forth, but also to emotional, social, and personality-related processes. A partial list of these networks is shown in table 2.2.

Table 2.2: Some Neural Networks Studied by Neuroimaging

Arithmetic
Autobiographical memory
Faces
Fear
Music
Object perception
Reading and listening
Reward
Self-reference
Spatial navigation
Working memory

Connectivity

As the studies of reading and brain activity show, several neural areas must be orchestrated to carry out any task. One approach to investigating this connectivity uses fMRI to study the timeline of activity and the correlations between active areas of the brain. Figure 2.2 illustrates the connectivity of the anterior cingulate during tasks that involve attention, such as reading and listening. This area of the brain has large-scale connectivity to many other brain areas and is ideally situated to exercise executive control over other brain networks (Posner, 2008).

The executive attention network resolves conflict among competing responses. For example, if you are asked to name the color of ink (such as blue) in which the word *red* is written, there is a conflict between the usual reading response and the instructed response to name the ink color. The executive attention network allows us to inhibit the word name while responding to the ink color. The anterior cingulate is part of this executive network. According to Bush, Luu, and Posner (2000), an analysis of a number of conflict tasks shows that the more dorsal, or rear, part of the anterior cingulate is involved in the regulation of cognitive tasks, while the more ventral, or front, part of the cingulate is involved in regulation of emotion. The dorsal part of the anterior cingulate has strong connections to frontal and parietal areas that are also involved in cognitive processes; during task performance, it establishes contact with these brain areas involved in processing information. In one study, for example, participants selected either visual or auditory information in separate blocks of trials. During the selection of visual information, the dorsal cingulate showed correlation with visual brain areas; during the selection of auditory information, it switched, showing correlation to auditory areas (Crottaz-Herbette & Mennon, 2006). In other studies involving emotional stimuli, the more ventral parts of the cingulate became active and became connected to limbic areas related to the emotion being processed (Etkin et al., 2006).

cognition

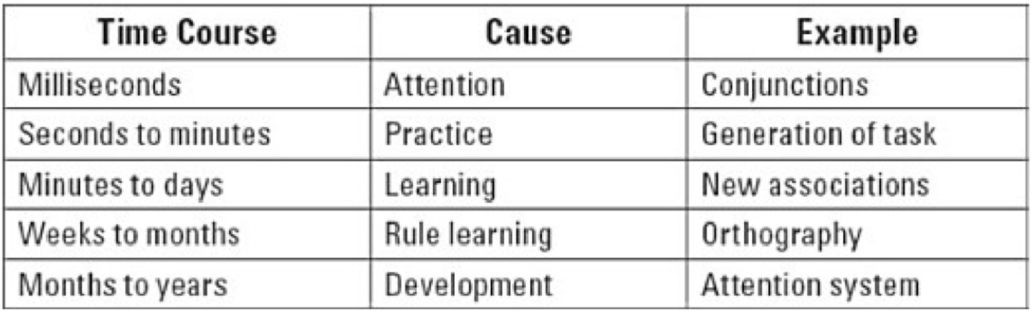
Prefrontal cortex

Anterior cingulate

Another approach to measuring connectivity uses noninvasive diffusion tensor imaging (DTI) to reveal the white matter fiber tracts that connect neural areas. This form of imaging measures the diffusion of water molecules in particular directions due to the presence of myelinated fibers (Conturo et al., 1999). Thus it provides a way to examine the physical connections in the brain and trace fiber pathways during different stages of human development.

As noted earlier, because fMRI is noninvasive, it is possible to use multiple scans of the same individual to examine changes that occur with learning and development (Kelly & Garavan, 2005). This obviously is an important tool for educational applications. It is common for learning on a task to decrease the number and extent of cerebral activation. The rate of these changes may vary from milliseconds to years, depending on what is being learned (see table 2.3 for time courses to acquire different kinds of learning). The connectivity of the involved networks also can be enhanced by practice (McNamara et al., 2007). Studies of changes in connectivity as an individual develops show that the local connections dominant in children are supplemented with the longer connections more prominent in adults (Fair et al., 2009). This process is often accompanied by a reduction in the number and extent of activations, as when practicing a given task.

Table 2.3: Time Required to Show Brain Changes Based on Different Causes



Time Course	Cause	Example
Milliseconds	Attention	Conjunctions
Seconds to minutes	Practice	Generation of task
Minutes to days	Learning	New associations
Weeks to months	Rule learning	Orthography
Months to years	Development	Attention system

Electromagnetic Imaging

Because fMRI depends upon changes in blood flow, it develops relatively slowly, and small differences over time may be hard to detect. However, the use of electrical activity recorded from the scalp in the form of the electroencephalogram (EEG) is an old method that can yield high temporal accuracy. Before the development of neuroimaging, it was not possible to tell from an EEG recorded at the scalp where the signal originated in the brain. However, by combining electrical or magnetic recording from outside the head with fMRI, it is possible to get high temporal *and* spatial resolution.

Event-Related Potentials

When a stimulus such as a word is presented many times, the electrical or magnetic activity can be averaged to eliminate the background, not time locked to the stimulus, and form an *event-related potential*. The event-related potential represents the effect of the stimulus on the brain millisecond by millisecond following the stimulus. It is a picture of the brain activity induced by the signal. For example, Dehaene (1996) used electrical recording from scalp electrodes to map out the time course of mental activity involved in determining whether a number shown visually was above or below five. He used a computer to display a sequence of numbers, which participants had to classify as above or below 5 by pressing a key, then averaged the brain electrical activity following the presentation of each number. During the first hundred milliseconds after the presentation of the input number, the visual system showed activity. When the input was an Arabic numeral (6), both hemispheres were active; when it was a spelled digit (*six*), however, activity was in the visual word form system of the left hemisphere that we described earlier. In the next hundred milliseconds, brain activity varied depending on how close to or far from 5 the number was. This effect of the distance from 5 was shown in the parietal brain areas known to be involved in representing the mental number line. Before the participant pressed the key to indicate above or below 5, electrodes above the motor areas were active. After pressing the key, if the person was in error (for example, had mistakenly indicated that the digit 6 was below 5), activity showed in the frontal midline near the anterior cingulate. Although being able to recognize the quantity of a number is a very elementary aspect of numeracy, training in the appreciation of the value of a number has been shown to be an important contributor to success in learning elementary school arithmetic (Griffin, Case, & Siegler, 1995).

Oscillations

The complex electrical signals coming from scalp electrodes can be separated by analysis into sine and cosine waves. There is a great deal of interest in these oscillations, both in how they show changes of brain state and integration of brain activity in different brain systems. During sleep, for example, deep slow waves predominate; in the awake resting state, created by closing the eyes, alpha frequency (about 10 Hz) dominates, particularly over electrodes at the back of the scalp. When someone realizes he or she has made an error, activity occurs in the theta electrical band (3 Hz) (Berger, Tzur, & Posner, 2006). It has been hypothesized that high-frequency gamma activity (40 Hz) is important in order to tie together distant brain regions that are analyzing a single object (Womelsdorf et al., 2007).

Infants and Young Children

Electrical recordings are sufficiently noninvasive to use with young children, which makes them valuable for understanding what happens in the brain during infancy. For example, infants come into the world already able to discriminate among the units of language (phonemes) in all languages. That is, if an infant hears one phoneme sounded over and over again (for example, *ba*), its novelty effects are reduced. However, a recovery of the novelty effect occurs when the infant discriminates a different phoneme (for example, *da*) from the *ba* that has just been repeated. Thus, the infant exhibits an auditory system that can discriminate between phonemes not only in his native language, but in all of the world's languages. In the period between six and ten months of age, there is considerable shaping of this phonemic structure (Kuhl, 2000). Those sounds to which the infant is exposed tend to solidify and form a unit, while the ability to discriminate unfamiliar sound units begins to disappear. Studies have shown that infants raised in English-speaking homes can maintain their ability to discriminate phonemes in Mandarin Chinese, for instance, if exposed to a speaker of those sounds during this period (Kuhl, Tsao, & Liu, 2003). In addition, phonemes in English (their native language) are also facilitated (Kuhl et al., 2006).

Unfortunately, the studies also revealed that learning did not occur when the language exposure was to a video rather than an actual person. Current research is attempting to determine the most important aspects of these social interactions between an infant and a tutor that facilitate language acquisition in the hope that they could be incorporated into an electronic media presentation. The tutor in these studies used elaborate methods to maintain the interest of the infant, and we simply do not know if these methods can be duplicated by a nonsocial, computer-based system. However, these findings and others like them show that the auditory system of infants is trained by the speech patterns of their community.

Experiments with infants have also shown that the effectiveness of this training can be measured by variations in the electrical signals that follow a change from a frequent to an infrequent phoneme (Guttorm et al., 2005; Molfese, 2000). As noted earlier, the brain shows its discrimination between the two phonemes by responding differently when the novel phoneme occurs. This electrical difference can be used to measure the efficiency of the brain in making the discrimination. Consequently, we can examine the effectiveness of caregivers in establishing the phonemic structure of their native language and other languages that they desire to teach. From these recordings, it is also possible to predict later difficulties in spoken language and reading (Guttorm et al., 2005; Molfese, 2000). It is still unknown exactly how accurate these predictions can be. Currently, brain stem electrical activity recorded from the scalp allows early detection of deafness in infants. Similarly, use of electrical recording should make it possible to check for the development of a strong phonemic structure even during infancy.

Lesions

Not all parts of an active brain network are needed to carry out a task. In the past, the effects of brain lesions have been studied as a primary way to identify brain areas that, when lost, will prevent a person from performing certain tasks. A good example of the use of lesion data in conjunction with imaging occurred in a study of a patient who had suffered a stroke. He was unable to read words when they were presented to the left of where he was looking (called *fixation*), but he could read them fluently when the words were presented to the right of fixation (Cohen et al., 2004). Imaging revealed an interruption of the neural fibers that conducted information from the right hemisphere occipital lobe (where visual signals are first processed) to the visual word form area (see fig. 2.1, page 31). Typically, the left visual field has direct access to the right hemisphere but must cross over the corpus callosum to access the left hemisphere. In this patient, when words were presented to the left of fixation (that is, presented directly to the right hemisphere of the brain), the patient could only sound them out letter by letter. He demonstrated that he had retained all of his reading skills, however, when words were presented to the right visual field (that is, presented directly to the left hemisphere—the visual word form area). This study illustrates the importance of the visual word form systems for fluent reading.

It is now possible to apply brief magnetic pulses (transcortical magnetic stimulation, or TMS) to the scalp overlying the brain area of interest to disrupt parts of a network at particular times in order to observe the effects on task performance. One striking finding of this technology showed that readers of Braille use the brain's visual system. When TMS was applied to the visual cortex, Braille readers had a specific problem in reading words, suggesting that the visual system was being used to handle spatial aspects of the tactile input from the Braille characters (Pascale-Leone & Hamilton, 2001).

Lesion data and imaging techniques can be used to confirm and extend theories on learning and brain development. While educators are not usually dealing with patients with specific brain lesions resulting from stroke, findings from these patients can often illuminate specific learning difficulties, such as dyslexia (problems with reading) or dyscalculia (problems with arithmetic).

Data from lesion studies may reveal causes of learning difficulties such as dyslexia and dyscalculia.

Genes: Individual Differences in Network Efficiency

Educators are interested in individual differences among students, and this interest has usually involved the study of intelligence(s). Neuroimaging has provided a new perspective on the nature of individual differences. Although most of the networks studied by neuroimaging (see table 2.2, page 32) are common to all people, their efficiency varies, which may be partly due to genetic variations. But the expression of these genetic variations is also influenced by experience. Genes code for different proteins that influence the efficiency with which modulators, such as dopamine, are produced and/or bind to their receptors. These modulators are in turn related to individual differences in the efficiency of one's brain networks.

Humans have much in common in the anatomy of their high-level networks, and this must have a basis within the human genome. The same genes that are related to individual differences are also likely to be important in the development of the networks that are common to all humans. Learning can build on pre-existing brain networks to achieve new functions. For example, primitive appreciation of number is present in infancy. However, when used together with language networks, this primitive sense of numeracy can form a basis for numerical calculation (Dehaene & Cohen, 2007).

In the study of attention, individual differences have been linked to differences in genetic variation. Recall that the executive attention network is involved in the resolution of conflict between other brain systems. The association of the executive attention network with the neuromodulator dopamine is a way of searching for candidate genes that might relate to the efficiency of the network. For example, several studies employing conflict-related tasks found that alternative forms (alleles) of the catechol-o-methyl transferase (COMT) gene were related to the ability to resolve conflict. A number of other dopamine genes have also proven to be related to this form of attention. In addition, research has suggested that genes related to serotonin transmission also influence executive attention (see Posner, Rothbart, & Sheese, 2007, for a review). In studies using brain imaging, it was also possible to show that some of these genetic differences influenced the degree to which the anterior cingulate was activated during the performance of a task. In the future, it may be possible to relate genes to specific points within neural networks, allowing a much more detailed understanding of the origins of brain networks.

While genes are important for common neural networks and individual differences in efficiency, specific experiences also play an important role. Several genes, for instance, including the DRD4 gene and the COMT gene, have been shown to interact with aspects relating to the quality of parenting. For example, one study (Sheese, Voelker, Rothbart, & Posner, 2007) found that in the presence of one version of the DRD4 gene, parents are influential in reducing the impulsivity of their two-year-olds. In children without that version of the gene, however, the quality of parenting did not influence impulsivity. This provides evidence that aspects of the culture in which children are raised can influence the way in which genes shape neural networks—ultimately influencing child behavior (Posner, 2008).

> Several genes have been shown to interact with aspects related to the quality of parenting.

If brain networks are affected by parenting and other cultural influences, it should be possible to develop specific training methods to influence underlying brain networks. For example, one study tested the effect of training during the period of major development of executive attention, which takes place between four to seven years of age. Training methods were adopted from primate studies and taught the children to manage conflict. Trained children showed an improvement in conflict resolution skills as well as changes in the underlying brain network—changes that generalized to an IQ test using materials quite different from those involved in the training. Similar studies have shown improvement of attention in classrooms that carry out training in executive function through working-memory training tasks as well as through meditation (see Rothbart et al., 2009, for a review of this work).

Given the wide range of individual differences in the efficiency of attention, it is expected that attention training could be especially beneficial for those children with poorer initial efficiency. These could be children with pathologies that involve attentional networks, children with genetic backgrounds associated with poorer attentional performance, or children raised in various degrees of deprivation.

Summary

Neuroimaging has provided a means of understanding how the human brain operates during tasks similar to those performed in school, such as reading and arithmetic. Networks of brain areas are connected to carry out most tasks of daily life. With practice, the connectivity between brain areas is strengthened, and tasks can be carried out more efficiently. Interrupting networks by temporary or permanent lesions can lead to loss of particular functions. The results of imaging studies have also provided important links between the general networks that are present in all people and the differences in the efficiency of these networks that lead to individuality. Much of the neuroimaging work so far deals with studies common to early education. However, the field is expanding to deal with differences between the expert and the novice brain (Anderson, 2007; Posner, in press). These studies should further expand the usefulness of imaging in secondary and higher education.

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Judy Willis

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Dr. Willis is a research consultant and member of the board of directors for the Hawn Foundation, an international foundation developed and directed by Goldie Hawn to implement educational programs in schools to teach students about their brains so they can lead smarter and happier lives. When not teaching, writing, consulting, or making presentations, Dr. Willis is a home winemaker and writes a weekly wine column.

In this chapter, Dr. Willis discusses how important it is for educators to understand the recent research in neuroscience that can have an impact on teaching and learning. Based on this research, she suggests a number of strategies that educators can consider in designing their instructional approaches that are likely to lead to improved student understanding and achievement.

Chapter 3

The Current Impact of Neuroscience on Teaching and Learning

Judy Willis

The convergence of laboratory science and cognitive research has entered our classrooms. Interpretations of this research and its implications for increasing the effectiveness of instruction are welcomed by many educators who seek ways to breathe life into increasingly compacted curricula that must be "covered" for standardized tests. Other teachers, who have been forced to use curricula claiming to be brain based that in fact are neither effective nor adequately supported by valid scientific research, are rightfully hesitant and cynical about using laboratory research as evidence on which to base classroom strategies.

In this chapter, I offer information about the brain processes involved in learning and memory to give educators foundational knowledge with which to evaluate the validity of "brain-based" claims. In addition, understanding how one's most successful lessons and strategies correlate with neuroscience research promotes the expansion and modification of these successful interventions for use in more situations and for the varying needs and strengths of individual students.

My background as an adult and child neurologist is the lens through which I evaluate the quality and potential applications of the new science of learning. However, it is my own schooling (I returned to school in 1999 to earn a teaching credential and Master of Education degree) and my past ten years of classroom teaching that allow me to incorporate the theoretical wisdom and observations of great educators, past and present, with laboratory analysis of neuroimaging, neurochemistry, and electrical monitoring of regions of the brain in response to different environmental influences and sensory input.

Pairing theoretical interpretations of observations about teaching and learning with the interpretations of the current laboratory research offers what I call “neuro-*logical*” strategies applicable to today’s classrooms.

A Brief Warning

It is striking how the accumulated scientific research since the early 1990s supports theories of learning from educational and psychological visionaries, such as William James, Lev Vygotsky, Jean Piaget, John Dewey, Stephen Krashen, Howard Gardner, and others. As I share stories of scientific support for these educational visionaries’ theories, I hope also to illuminate the pathways through the brain that we see through neuroimaging.

However, the neuroscience implications of brain and learning research for education are still largely suggestive rather than empirical in establishing a solid link between how the brain learns and how it metabolizes oxygen or glucose. Teaching strategies derived from well-controlled neuroimaging research are at best compatible with the research to date about how the brain seems to deal with emotions, environmental influences, and sensory input.

Although what we see in brain scans cannot predict exactly what a strategy or intervention will mean for individual students, the information can guide the planning of instruction. I use the term *neuro-logical* in referring to strategies suggested by research and consistent with my neuroscience background knowledge that I correlate with research implications and have applied successfully in my own classrooms.

Although what we see in brain scans cannot predict exactly what a strategy or intervention will mean for individual students, the information can guide the planning of instruction.

Learning Life Support

Research can suggest the most suitable emotional, cognitive, and social environments for learning. It is up to professional educators with knowledge about the brain to use the findings from scientific research to guide the strategies, curriculum, and interventions they select for specific goals and individual students. Knowing the workings of the brain makes the strategies we already know more adaptable and applicable.

When educators learn about how the brain appears to process, recognize, remember, and transfer information at the level of neural circuits, synapses, and neurotransmitters, and then share that knowledge with students, the empowerment for both enriches motivation, resilience, memory, and the joys of learning. The purest truth, I suggest, is the least open to statistical analysis and comes not from my twenty years as a physician and neuroscientist, but from my past ten years as a classroom teacher. There is no more critical life support than passionate, informed teachers who resuscitate their students' joyful learning.

This chapter describes the evolution of several current neuroscience-to-classroom topics in which interpretations of the new sciences of learning correlate strongly with past theories that were based on observations of students without the benefit of looking into their brains. A look backward and forward at the lab-to-classroom implications of attention, emotion, and neuroplasticity theories and research suggests practical implications for instruction, curriculum, and assessment for today's learners—tomorrow's 21st century citizens.

The Neuroscience of Joyful Learning Emotions

Remember the adage, "No smiles until after winter holidays"? Do you recall the time when proper learning behavior was represented by students sitting quietly, doing exactly what they were told without question or discussion, and reporting back memorized facts on tests? Where did those notions come from? Certainly not from the education luminaries of the past. A few thousand years ago, Plato advised against force-feeding facts to students without providing opportunities for them to relate learning to interest or evaluating their readiness:

> Calculation and geometry and all the other elements of instruction . . . should be presented to the mind in childhood; not, however, under any notion of forcing our system of education. Because a freeman ought not to be a slave in the acquisition of knowledge of any kind. Bodily exercise, when compulsory, does no harm to the body; but knowledge which is acquired under compulsion obtains no hold on the mind. (Plato, trans. 2009, p. 226; italics added)

Jump ahead several thousand years, and we discover Lev Vygotsky's zone of proximal development (ZPD) theory. He suggested that students learn best when guided by adults or more capable peers through the distance between their level of independent problem solving and their level or zone of potential development (Vygotsky, 1978). Similarly, Stephen Krashen (1981) supported the need for individualizing and differentiating instruction in the ZPD, which he called “comprehensible input.” Krashen also described the negative effect of stress on learning: “Language acquisition does not require . . . tedious drill. The best methods supply comprehensible input (a bit beyond the acquirer’s current level) in low anxiety situations, containing messages that students really want to hear” (Krashen, 1982, p. 25).

Incremental, Achievable Challenge

The compelling nature of computer games is an excellent example of the success of differentiating instruction to the students’ ZPD or level of comprehensible input. Studies of what makes computer games so captivating show that variable challenge, based on the player’s ability, is the key element (Reigeluth & Schwartz, 1989).

The most popular computer games take players through increasingly challenging levels. As skill improves, the next challenge motivates practice and persistence because the player feels the challenge is achievable. Similar incremental, achievable challenges in the classroom, at the appropriate level for students’ abilities, are motivating and build mastery by lowering the barrier, not the bar.

In computer games, the degree of challenge for each level is such that players are neither bored nor overwhelmed and frustrated. Practice allows players to improve and thus experience the neurochemical response of pleasure. Players succeed at the short-term goals provided by multiple levels of incremental challenge, while moving toward the long-term goal of completing the game. This is the power of achievable challenge: opportunities for students to see their effort-related improvement along the way to an ultimate goal, instead of having only the feedback of a final test or other end-point assessment. The computer game does not give prizes, money, or even pats on the back, yet it remains compelling. This may be attributed to the powerful brain response to intrinsic reward, described in the next section as the dopamine-reward effect.

Incremental, achievable challenges in the classroom, at the appropriate level for students’ abilities, are motivating and build mastery by lowering the barrier, not the bar.

Before the research on the dopamine-reward system, it was Krashen’s theory of an affective (emotion-responsive) filter that started my search for how the brain's physical structures or neurochemicals are influenced by emotions. Research now supports recommendations to avoid high-stress instructional practices such as use of fear of punishment and to incorporate appropriate environmental, social, emotional, and cognitive considerations into instruction. We recognize that the brain has filters that influence what information enters our neural networks, as we see the effects of stress and other emotions on these filters.

Neuroimaging studies (Pawlak, Magarinos, Melchor, McEwen, & Strickland, 2003) show how stress and pleasure influence the way the brain filters sensory input and the effects of such emotions on the amygdala (Krashen's affective filter), a gateway that sends input either to the thinking brain (the prefrontal cortex) or to the lower, involuntary reactive brain. When stress directs sensory input to the lower brain, that input is not available for higher cognitive processing. To reduce the stress of frustration and increase information processing and memory at the higher cognitive level, we can encourage students by recognizing effort as well as achievement and providing opportunities for them to work at their achievable challenge level.

Intake Filters

The brain's first sensory intake filter, the reticular activating system (RAS), is a primitive network of cells in the lower brain stem through which all sensory input must pass if it is to be received by the higher brain. Out of the millions of bits of sensory information available to the brain every second, only several thousand are selected to pass through the RAS—and that selection is an involuntary, automatic response rather than a conscious decision. Much as in other mammals, in humans, the RAS is most receptive to the sensory input that is most critical to survival of the animal and species. Priority goes to changes in the individual's environment that are appraised as threatening. When a threat is perceived, the RAS automatically selects related sensory information and directs it to the lower, reactive brain, where the involuntary response is fight, flight, or freeze (Raz & Buhle, 2006). The RAS is an editor that grants attention and admission to a small fraction of all the sensory information available at any moment. This survival-directed filter is critical for animals in the wild, and it has not changed significantly as humans evolved.

Implications for the Classroom

The implications for the classroom are significant. Reducing students' perception of threat of punishment or embarrassment in front of classmates for not doing homework, concern about whether they will be chosen last for a kickball team, or anxiety that they will make an error in front of classmates because they are not fluent in English is not a “touchy-feely” option. During stress or fear, the RAS filter gives intake preference to input considered relevant to the perceived threat, at the expense of the sensory input regarding the lesson (Shim, 2005). Unless the perception of threat is reduced, the brain persists in doing its primary job—protecting the individual from harm. During fear, sadness, or anger, neural activity is evident in the lower brain, and the reflective, cognitive brain (prefrontal cortex) does not receive the sensory input of important items, such as the content of the day’s lesson.

Neuroimaging has also given us information about which sensory input gets through the RAS when no threat exists. The RAS is particularly receptive to novelty and change associated with pleasure and to sensory input about things that arouse curiosity. Novelty—such as a changed room arrangement, a new wall or display color, discrepant events, posters advertising upcoming units, costumes, music playing when students enter the room, and other curiosity-evoking events—alerts the RAS to pay attention because something has changed and warrants further evaluation (Wang et al., 2005).

Students are often criticized for not paying attention when they may simply not have their RAS attuned to what their teachers think is important. Knowing how the RAS works means we can promote learning communities in which students feel safe and can count on adults to consistently enforce the rules that protect their bodies, property, and feelings from classmates or others who threaten them.

Priming the RAS

Our increasing understanding about what gains access through the RAS once a threat (stress) is removed also offers clues to strategies that promote attentive focus on lessons (Raz & Buhle, 2006). The following are a few examples of how you can build novelty into learning new information:

- Modulate your voice when presenting information.
- Mark key points on a chart or board in color.
- Vary the font size in printed material.
- Change seating arrangements periodically.
- Add photos to bulletin boards.

- Advertise an upcoming unit with curiosity-provoking posters, and add clues or puzzle pieces each day. Then ask students to predict what lesson might be coming. This can get the RAS primed to select the sensory input of that lesson when it is revealed.
- Play a song as students enter the room to promote curiosity and focus, especially if they know that there will be a link between some words in the song and something in the lesson.
- Behave in a novel manner, such as walking backwards at the start of a lesson about negative numbers. Curiosity primes students' RAS to follow along when you then unroll a number line on the floor to begin that unit about negative numbers.

Other RAS alerting strategies include engaging curiosity by asking students to make predictions. For example, you can get the RAS to focus on a lesson about estimating by overfilling a water glass. When students react, you respond, "I didn't estimate how much it would hold." Even a suspenseful pause before saying something particularly important builds anticipation as students become alert to the novelty of silence and the RAS is prompted by curiosity about what you will say or do next.

Similarly, there may be several minutes of curious excitement when students enter the classroom and find, say, a radish on each desk. A radish? The students' RAS will be curious, and so their attention will promote intake of sensory input cues to the puzzle of this novel object on their desk. They will be engaged and motivated to discover why the radishes are there. Younger students, learning the names and characteristics of shapes, now have the opportunity to develop a concept of roundness and evaluate the qualities that make some radishes rounder than others.

The radish lesson for older students might address a curriculum standard, such as analysis of similarities and differences. Their RAS will respond to the color, novelty, and peer interaction of evaluating the radishes they usually disdain in their salads. In the meantime, students develop skills of observation, comparison, contrast, and even prediction as to why the radish that seemed so familiar at first reveals surprises when examined with a magnifying glass. Stress levels remain low when students can choose their individual learning strengths to individually record their observations using sketches, verbal descriptions, or graphic organizers (such as Venn diagrams). They then feel they have something to contribute when groups form to share observations about what the radishes in their group have in common and how they differ.

As a survival mechanism, the RAS admits sensory input associated with pleasure. Animals have adapted to their environments and seek to repeat behaviors that are pleasurable and survival related, such as eating tasty food or following the scent of a potential mate. Engaged and focused brains are alert to sensory input that accompanies the pleasurable sensations. These associations increase the likelihood of the animal finding a similar source of pleasure in the future. As students enjoy the investigation with the radishes, the required lesson content can flow through the RAS gateway to reach the higher, cognitive brain.

A novel experience also has a greater chance of becoming a long-term memory because students are likely to actually answer their parents' often-ignored queries about what they learned in school that day. Students will summarize the day's learning as grateful parents give the positive feedback of attentive listening. The effect of the radish as a novel object—something parents probably never expected to hear described by their child—now alerts the parents' RAS, and the stage is set for a family discussion of the lesson.

Where Heart Meets Mind

Neuroimaging reveals that the amygdala and associated neural networks function very much like Krashen's affective filter, reducing successful learning when students are stressed. Until recently it was thought that the amygdala responded primarily to danger, fear, or anger. But neuroimaging studies show that it also responds to positive emotional influences. In experiments using fMRI (Pawlak et al., 2003), subjects were shown photographs of people with happy or grumpy expressions. After viewing the faces, the subjects were shown a list of words and instructed that the words would then appear mixed into a longer series of words. If they recognized a word from the initial list, they were to respond with a clicker. The results revealed better recall by subjects who viewed the happy faces, and their scans during recall had higher activity in the prefrontal cortex (PFC).

Neural networks converge in the PFC to regulate cognitive and executive functions, such as judgment, organization, prioritization, risk assessment, critical analysis, concept development, and creative problem solving. Unlike the RAS, which is proportionately the same size in humans as in other mammals, the PFC is proportionally larger in humans than in other mammals. For learning to occur and be constructed into conceptual long-term knowledge, sensory input needs to pass through the RAS and be processed by the PFC.

For learning to occur, sensory input needs to pass through the RAS and be processed by the prefrontal cortex.

The subjects in these studies who viewed the grumpy faces showed increased metabolic activity in the amygdala, but significantly lower activity in the PFC than was exhibited by the control group when recalling the words they were instructed to remember. The studies suggest that when we are in a negative emotional state, the amygdala directs input to the lower, reactive (fight/flight/freeze) brain. When the subjects viewed pleasant faces, the metabolic activity was lower in the amygdala and higher in the reflective PFC, suggesting the nonthreatening condition favors conduction of information through the amygdala networks to the PFC (Pawlak et al., 2003).

The Influence of Dopamine

Dopamine is one of dozens of neurochemicals and hormones that not only influence learning, but also can be activated by certain environmental influences and teaching strategies. Dopamine is one of many neurotransmitters that carry information across gaps (synapses) between the branches (axons and dendrites) of connecting neurons. Certain experiences have been associated with the increased release of dopamine, which in turn produces pleasurable feelings. Engaging students in learning activities that correlate with increased dopamine release will likely get them to respond not only with pleasure, but also with increased focus, memory, and motivation (Storm & Tecott, 2005).

What Goes Up Must Come Down—Even in the Brain

Just as dopamine levels rise in association with pleasure, a drop in dopamine can be associated with negative emotions. A dopamine storage structure located near the prefrontal cortex, called the *nucleus accumbens* (NAcc), releases more dopamine when one's prediction (one's choice, decision, or answer) is correct and less dopamine when the brain becomes aware of a mistake. As a result of the lowering of dopamine, pleasure drops after making an incorrect prediction. When an answer is correct, the increased release of dopamine creates positive feelings (Salamone & Correa, 2002). This set of effects makes dopamine a learning-friendly neurotransmitter, promoting motivation, memory, and focus along with pleasurable feelings. It allows us to put a positive value on actions or thoughts that resulted in the increased dopamine release, and the neural networks used to make the correct predictions are reinforced. Just as valuable is the modification of the network that was used to make an incorrect prediction; the brain wants to avoid the drop in pleasure the next time. However, there needs to be timely corrective feedback for this memory storage correction to take place (Galvan et al., 2006).

This dopamine-reward system explains the compelling aspects of achievable challenge in computer games. When players make progress toward the achievement of their goals and feel the pleasure of the dopamine reward for their correct decisions (that is, their actions, choices, or answers), they remain intrinsically motivated to persevere through the next challenges of the game (Gee, 2007). Similarly, when students experience the dopamine pleasure of a correct prediction in class, they are intrinsically motivated to persevere through the challenges and apply effort to reach the next level of learning (O'Doherty, 2004).

The increased dopamine release in response to the satisfaction of a correct response reinforces the memory of the information used to answer the question, make a correct prediction, or solve the problem. The brain favors and repeats actions that release more dopamine, so the involved neural memory circuit becomes stronger and is favored when making similar future choices. However, if the response is wrong, then a drop in dopamine release results in some degree of unpleasantness. The brain responds negatively to mistake recognition by altering the memory circuit to avoid repeating the mistake and experiencing another drop in the dopamine pleasure (Thorsten et al., 2008).

When students experience the dopamine pleasure of a correct prediction in class, they are motivated to persevere through the challenges of the next level of learning.

The value of the brain's dopamine disappointment response is associated with brain changes through neuroplasticity. Neuroplasticity is the ability of neural networks to extend, prune, reorganize, correct, or strengthen themselves based on acquiring new information, obtaining corrective feedback, and recognizing associations between new and prior knowledge. Changes in the neural circuits develop so that the brain is more likely to produce a correct response the next time and avoid the pleasure-drop consequences of making a mistake (van Duijvenvoorde et al., 2008).

Reducing the Fear of Mistakes

We know that understanding increases with corrective feedback after the brain makes incorrect predictions. However, making predictions means taking the risk of participating and being wrong, and most students' greatest fear is making a mistake in front of their peers. In order to construct and strengthen memory patterns (networks) of accurate responses and revise neural networks that hold incomplete or inaccurate information, students need to participate by predicting correct or incorrect responses. The goal is to keep all students engaged and participating because *only the person who thinks, learns*.

Students who risk making mistakes benefit from the dopamine pleasure fluctuations. The dopamine response to correct or incorrect predictions increases the brain's receptivity to learning the correct response. When immediate corrective feedback follows the students' incorrect predictions, the brain seeks to alter the incorrect information in the neural network that resulted in the wrong prediction so as to avoid the mistake in the future.

The Value of Frequent Assessment

Frequent formative assessment and corrective feedback are powerful tools to promote long-term memory and develop the executive functions of reasoning and analysis. Frequent assessment provides teachers information about students' minute-to-minute understanding during instruction. Your awareness of students' understanding from the ongoing feedback allows you to respond and adjust instruction accordingly so students do not become frustrated by confusion and drop into the fight/flight/freeze mode, in which cognitive processing and learning lesson content cannot take place.

For the process of assessment and expedient feedback to work, students must participate. The interventions I suggest are twofold: first, keep students' amygdala pathway open to the PFC and reduce their fear of participation. When students are in this low-anxiety state, they remain engaged, participate, and learn from feedback provided in a nonthreatening manner. Second, obtain frequent assessment of individual students' understanding throughout the class period without calling on specific students. For example, ask whole-class questions with single-word or multiple-choice (by letter) answers, and then have students respond by writing on individual whiteboards. Students need only hold up their whiteboards long enough for you to see their responses and nod to signify you have seen them.

About every ten minutes, do a walkabout and respond to the whiteboard assessments. This will allow you to prompt students whose responses demonstrate understanding to move on to preplanned higher-challenge activities while you work with those who need further explanation or practice. The students at mastery level are no longer stressed by the frustration of repeated explanation, drill, and grill on information they already know. Instead, these students can discuss a challenge question with a partner, create a graphic organizer comparing the new material to prior knowledge, or predict how what they learned can be transferred to other uses related to their interests. When the whiteboard assessment/feedback process becomes a regular part of the class, the amygdala-stressing frustration of confusion or boredom is reduced because students know within a few minutes that they will have help in acquiring the understanding needed to proceed or opportunities to move on to an enrichment activity in their higher achievable challenge range.

Positivity

Strategies to promote input to the prefrontal cortex overlap with those associated with increased dopamine levels. Examples of these amygdala-friendly and dopamine-releasing interventions include:

- Allowing students to move around in class periodically in learning activities. Examples are using pantomime while they guess which vocabulary word is being enacted or doing a ball toss to review high points of a lesson.
- Reading to students or shared reading by student pairs
- Creating opportunities for students to experience intrinsic satisfaction from incremental progress, not just feedback after final product (test, project, or report) assessment
- Using humor, not sarcasm
- Structuring positive peer interactions
- Using well-planned collaborative group work
- Providing some opportunities for student choice of practice or assessment options

Mind Controls Matter Through Neuroplasticity

Scientists are certainly on to something regarding neuroplasticity, and I enjoy reading current claims about this concept that has been in use for over a hundred years. Neuroplasticity changes neural networks by adding or pruning synapses and dendrites and producing layers of insulating myelin around axons. The construction of stronger, more efficient networks (faster retrievals, greater transfer) in long-term memory is stimulated by repeated activation of the circuit, such that *practice makes permanent* (Rivera, Reiss, Eckert, & Menon, 2005; Sousa, 2006).

This neuroplasticity information, shared with students by teaching them a "Brain Owner's Manual," has significantly increased my students' motivation to study and review. When you share with students that their brain networks and memories are strengthened with the neural activation of review and practice, just as their muscles strengthen with repeated exercise, they begin to believe you when you tell them, "This can be the last time you'll ever have to learn what a least common denominator is."

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A great study to share is the example of the neuroplasticity in the visual cortex. When we develop memory from visual information, the memory is ultimately stored in the cortex of the occipital lobes, located at the back of the brain. When we gain information by touching something, that sensation is recognized, and the memory ultimately stored in the parietal lobes at the top of the brain.

However, when subjects were blindfolded for a week and received intense tactile-sensory Braille practice, their occipital visual cortex, which before the experiment did not respond to tactile stimuli, demonstrated new neural-circuit plasticity and fMRI activity. Their visual cortex became similar to those found in people blind from birth (Merabet et al., 2008).

Pattern Development for More Successful Prediction

The extension and modification of neural network connections follows the patterning theories described by Piaget (Ginsberg & Opper, 1988). When students' knowledge increases through pattern recognition and by matching new information to memories, the neural networks become more extensive. Further modification, correction, and strengthening of the networks continue because of the dopamine feedback in response to accuracy of predictions (discussed earlier). Whenever students participate in a mental or physical activity that activates a specific pathway of neurons, the pattern that binds the connections is strengthened. When new information is added to the pattern, the network is extended, and future predictions (answers or choices) are more accurate (Dragansk & Gaser, 2004).

Patterning and Memory

To survive successfully, we need to collect information from the environment. Our brains perceive and generate patterns and use these patterned networks to predict the correct response to new stimuli. *Patterning* refers to the meaningful organization and categorization of information. Sensory data that pass through the brain's filters need to be successfully encoded into patterns that can be connected to existing neuronal pathways. The brain evaluates new stimuli for clues that help connect incoming information with stored patterns, categories of data, or past experiences, thereby extending existing patterns with the new input.

Strategies for Enhancing Pattern-Based Memory

When sensory input reaches the hippocampus—a structure located next to the amygdala—it is available for consolidation into memory. For consolidation to occur, prior knowledge from stored memory must be activated and transferred to the hippocampus to bind with the new information (Davachi & Wagner, 2002; Eldridge, Engel, Zeineh, Bookheimer, & Knowlton, 2005).

Using strategies that help students relate new information with memories they have already acquired enables students to detect the patterns and make connections. Such strategies include:

- Making analogies and recognizing similarities and differences
- Brainstorming about what they already know and what they want to learn about a new unit
- Administering pre-unit assessments, self-corrected for corrective feedback, and not counted for grading purposes
- Having class discussions, particularly using current events of high interest so that students can relate the new unit to prior knowledge
- Using ball-toss activities, in which students say what they think they know or make predictions about an upcoming topic or a book they will read
- Making cross-curricular connections, such as examining what students learned about the topic from the perspective of another class or subject
- Using activities that build pattern recognition skills. This is especially beneficial for younger students. For example, ask students to guess the pattern you are using as you call on students with a similar characteristic

(such as asking students wearing blue shirts to stand up one at a time until students predict what they have in common). You can give examples and nonexamples of a concept and ask students to make predictions about the category or concept that the items share.

- Using graphic organizers, because they are nonlinguistic visual, pictorial, or diagrammatic ways to organize information so that the student's brain discovers patterns and relationships
- Using multisensory learning, which extends patterns because stimulation promotes the growth of more connections between dendrites and more myelination. Each of the senses has a separate storage area in the brain. In multisensory learning, more areas of the brain are stimulated (Wagner et al., 1998). Activities that use multiple senses mean duplicated storage of information and thus more successful recall (Rivera et al., 2005).

When new information is recognized as related to prior knowledge, learning extends beyond the domain in which it occurred. It is available through transfer to create new predictions and solutions to problems in other areas beyond the classroom or test.

Yes, You Can Change Your Intelligence

Children, as well as many adults, mistakenly think that intelligence is determined at or before birth by their genes and that effort will not significantly change their potential for academic success. Especially for students who believe they are "not smart," the realization that they can literally change their brains through study and review strategies is empowering. This is also true of my neurology patients who lose function as a result of brain disease or trauma. Through practice, beginning with visualizing of moving the paralyzed limb or imagining themselves speaking, neuroplasticity constructs new neural networks as undamaged parts of their brains take over the job of the damaged regions (Draganski, Gaser, Busch, & Schuierer, 2004).

Intelligence can be considered as a measure of students' ability to make accurate connections between new input and existing patterns of stored information. As children grow and learn, they expand their experiential databases. The more experiences they have, the more likely their brains will find a fit when comparing new experiences with previous ones. These connections allow them to acquire and apply the new knowledge to solve problems. In this way, more successful, extensive patterning leads to more accurate predictions (answers). Through practice, experience, and mental manipulation, the brain builds intelligence (more accurate predictions) by extending, correcting, and strengthening neural networks.

Through practice, experience, and mental manipulation, we develop intelligence by extending, correcting, and strengthening neural networks.

A great positivity-building tool comes from students' learning about their brain's ability to change through this neuroplasticity process. When students understand that their brains can develop stronger, more efficient, accessible, and durable neural networks through their actions, they have the positivity, resilience, and motivation to do their part to develop the skills, knowledge, and intelligence to achieve their goals. Teachers can help their students recognize how effort and practice change their brains, resulting in improved memory, information retrieval, and knowledge transfer so that learning in one setting can readily be applied to new situations. I explain to my students: "Your own mental efforts in all types of higher thinking, practicing and reviewing, as well as making conscious choices to delay immediate gratification, working to achieve goals, and evaluating the strategies you used when you were most successful actually build your brain into a more efficient and successful tool that you control."

I have been teaching my upper elementary and middle school students about the brain filters that determine what information reaches their higher, thinking brains (PFC) and how they can consciously influence those filters. They learn about changes in their brains that take place through neuroplasticity. I show them brain scans, and we draw diagrams and make clay models of connections between neurons that grow when they learn new information. I call their lesson summaries "Dend-Writes," and we discuss how more dendrites grow when information is reviewed. I even send home electron microscope photos of growing dendrites and synapses and assign students to explain the neuroanatomy to family members and report their families' responses, because teaching new learning to someone else is strong memory cement.

I use sports, dance, and musical instrument analogies. I ask them to recall how their basketball shots or their guitar or ballet performances improved when they practiced more. Then we discuss that their brains respond the same way when they practice their multiplication facts or reread confusing parts of a book because, through neuroplasticity, practice makes permanent. Their results are wonderful. One ten-year-old boy said, "I didn't know that I could grow my brain. Now I know about growing dendrites when I study and get a good night's sleep. Now when I think about playing video games or reviewing my notes, I tell myself that I have the power to grow brain cells if I review. I'd still rather play the games, but I do the review because I want my brain to grow smarter. It works and feels great."

The Future

The most rewarding jobs of this century will be those that cannot be done by computers. The students best prepared for these opportunities need conceptual thinking skills to solve problems that have not yet been recognized. For 21st century success, students will need a skill set far beyond the current subject matter evaluated on standardized tests. The qualifications for success in the world that today's students will enter will demand the abilities to think critically, communicate clearly, use continually changing technology, be culturally aware and adaptive, and possess the judgment and open-mindedness to make complex decisions based on accurate analysis of information. The keys to success for today's students will come through the collaboration of the laboratory scientist and the classroom teacher.

The Science

Neuroscience is showing us more of the brain's potential to modify intelligence through neuroplasticity. With increasing developments in the genetic-environmental connection, fMRI scanning, and collaboration among neuroscientists, cognitive scientists, and all professionals in the mind, brain, and education fields, we will continue to add to our understanding of how different people learn and the role of environment and experience. We will have more predictive information earlier to enable individualizing learning for each student. With a better understanding of the brain's information-processing functions, neurotransmitters, and which networks do what, we will know more about the strategies best suited for different types of instruction.

Technology will surely play an increasing role in the classrooms of tomorrow. Already more online classes and computerized instruction (especially for foundational knowledge at all grade levels) are in use than ever before, and the possibilities for the future seem almost infinite. Models are developing to use neuroimaging, EEG, and cognitive evaluations to predict the best instructional modes for individual students.

Collaboration

An equally exciting trend is the development of learning communities within schools or districts, in which classroom teachers, resource specialists, and administrators use books and videos and share information from professional development workshops to evaluate strategies appropriate for students' needs. Educators who teach and observe classrooms discuss their successful use of these strategies, and teachers collaborate and reflect on neuro-*logical* strategies they try in their classrooms that appear to result in identifiable patterns of learning benefits.

In the learning communities I observe when I travel, I see dedicated professionals who chose to become educators because of their dedication to making a difference for all students. Teachers are drawn to their career choices for admirable reasons. Creativity, imagination, perseverance, and motivation endure in the educators I meet, even in these times of teacher blame and overpacked curriculum.

I observe as educators coach one another in research-based strategies and share the knowledge they acquire about the science of learning, and how they have or want to apply new research implications to further enhance students' positive and successful learning experiences. I see these groups then go beyond the boundaries of their schools and contribute to the growing global teacher-researcher community.

Increasingly it is evident that the most valuable assets for improving education won't be developed through neuroimaging in a laboratory, but rather by improving the effectiveness of educators. Given access to tools—time, ongoing professional development to acquire foundational knowledge about the science of learning, and professional learning communities to evaluate and share potential classroom applications of laboratory research about mind, brain, and education—educators will be the leaders in raising the level of preparation, optimism, and outcomes of the students who pass through their classrooms.

The interface of science and learning can continue to guide educators in the development of the strategies, interventions, and assessments to prepare today's students for the world of tomorrow. The more educators know about the research-supported basis for a strategy or procedure, the more they feel invested in it and the more comfortable they are using and modifying the strategy. This empowers and encourages teachers to extend lessons beyond rote memory into conceptual understanding and transferable knowledge. These educators help students become lifelong learners because they embrace the neuroscience of joyful learning.

Collaboration will propel the education advancements of this century. The one-way street of scientists telling teachers what to do, without having spent time observing in classrooms, has been modernized to a bridge between classroom and laboratory. The future developments with the most extensive and useful classroom applications will likely arise from input that educators provide to scientists. Through this collaboration, the seeds planted in a single classroom by a creative, resourceful teacher may be analyzed, replicated, expanded, and disseminated to benefit students worldwide. After all, isn't sharing what we teachers do so well?

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