Chapter 3

The Current Impact of Neuroscience on Teaching and Learning

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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.

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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.

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.

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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.

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.

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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.

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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).

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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). ?

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.*

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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).

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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."

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.

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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 over-packed 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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