Neuroscience Bases of Learning

M H Immordino-Yang, University of Southern California, Los Angeles, CA, USA
K W Fischer, Harvard University Graduate School of Education, Cambridge, MA, USA

Glossary

Domain – A culturally constructed area of knowledge, such as language, math, music, or social interaction.
Neural network – A set of neurons that are structurally and functionally interconnected so that they activate in coherent patterns associated with mental functions.
Neuroimaging – A variety of research techniques, some invasive and some not, concerned with measuring and mapping the physiology and structure of the brain.
Neuromyth – A misguided, oversimplified, or incorrect tenet in education that concerns the brain or neuroscience.
Skill – An ability to behave or think in an organized way in a particular context.

Beyond Neuromyths: Mind, Brain, and Education Is a Cross-Disciplinary Field

All human behavior and learning, including feeling, thinking, creating, remembering, and deciding, originate in the brain. Rather than a hardwired biological system, the brain develops through an active, dynamic process in which a child's social, emotional, and cognitive experiences organize his or her brain over time, in accordance with biological constraints and principles. In the other direction, a child's particular neuropsychological strengths and weaknesses shape the way he or she perceives and interacts with the world. Like the weaving of an intricate and delicate web (Fischer and Bidell, 2006), physiological and cultural processes interact to produce learning and behavior in highly nuanced and complex patterns of human development.

People in the field of education often begin with a preconception that biology refers to traits that children are born with, that are fixed and unfold independent of experience, while children's social and cultural experiences, including schooling, are at the mercy of these biological predispositions, somehow riding on top of, but not influencing, biology. However, current research in neuroscience reinforces the notion that children's experiences shape their biology as much as biology shapes children's development. The fields of neuroscience and more broadly biology are leading education toward analyzing the dynamic relationship between nurture and nature in development and schooling. A more nuanced understanding of how biology and experience interact is critically relevant to education. As neuroscientists learn about which aspects of experience are most likely to influence biology and vice versa, educators can develop increasingly tailored educational experiences, interventions, and assessments.

Due to this bi-directional relationship between a child's biological predispositions and social and cognitive experiences, the fields of neuroscience and education are coming increasingly into a research partnership. This relationship can be studied at many levels of analysis, from the workings of genes inside cells to the workings of communities inside cultures. However, in order for new information about the brain and learning to influence the design of learning environments, teachers and others involved in educational policy and design need to know about the newest principles about the brain and learning. Likewise, neuroscientists need to investigate phenomena that are relevant to real-world learning and development. To these ends, a new field has gradually taken shape over the last few years: mind, brain, and education (MBE). As a field, MBE encompasses educational neuroscience (a branch of neuroscience that deals with educationally relevant capacities in the brain), philosophy, linguistics, pedagogy, developmental psychology, and others.

In this interdisciplinary and applied climate, educators are in a particularly good position to help generate new questions and topics for research on learning and the brain, as they deal on a daily basis with the developmental issues and situations that affect real children and adults in their learning. For this reason, educators including teachers should have some familiarity with neuroscience and brain functioning, in order to become more informed consumers of educationally relevant findings as well as, ideally, contributors who help identify and shape new questions for neuroscience to pursue. For example, teachers can use information on the development of networks for numeric processing to design more effective curricula to teach math concepts, and educational assessments of students' math learning can help to shape new scientific questions about the development of math networks.

However, this does not mean that neuroscience is capable of contributing insights into all educational problems.

One of the challenges for the new field of MBE is for educators to learn about the applicability, implications, and limits of neuroscience research methods to various sorts of educational questions, and for neuroscientists at the same time to learn about the problems, issues, and processes of education, so that the two fields can collaborate as profitably as possible. For this to happen, educators and educational researchers need to know something about the tools, techniques, assumptions, and approaches that guide neuroscience research on learning, and need to develop a critical ability to consume and digest neuroscience findings and evaluate them for their potential applicability in the classroom. Toward this goal, teacher-training programs are beginning to incorporate information about the science of learning into their course offerings, and several new graduate programs in MBE have been launched at major universities in several countries in the last few years.

Before proceeding further, we felt the need to insert a strong cautionary note. As is typical during periods of rapid discovery, technological innovation, and theoretical advance, the field of MBE, as well as other related fields seeking to apply brain science to mainstream societal issues, are experiencing a lag between new technologies and findings on the one hand and the ability to interpret these findings on the other. In recent years, multiple examples of brain research misapplied have gone forward, including, for example, the overt labeling of elementary students as different categories of learners, from kinesthetic to auditory and beyond. Indeed, the scientific community agrees that much of what has been called brain-based education rests on very shaky ground. There is a proliferation of books written by nonscientists about the applications of neuroscience to learning, and while some of these books might present useful interpretations of neuroscience for educators, many of them suffer from a lack of basic understanding about the meaning and limitations of neuroscience research on learning and related processes. These books should be read with skepticism, as they often present models that are so oversimplified as to be misleading or even harmful or dangerous to children.

Overall, major changes in neuroscience research methods and theory are allowing better applicability of brain findings to educational issues and questions, and new insights into the processes that happen in schools. In this article, we focus on the prominent contribution of neuroimaging to the current view of learning as the construction of distributed neural networks that support skills, and how the development and recruitment of these neural networks is modulated and facilitated by domain-general processes in the brain, including emotion, attention, and mechanisms of social learning. We conclude with a call for further research that evaluates neuroscientific principles as they play out in classroom contexts.

New Neuroscience Methods Bring New Information and New Challenges for Interpretation

Educators' views of brain research have shifted in the past few years. While many educators continue to cling to so-called neuromyths, neuroscientists in the MBE field have been working to dispel these myths. In particular, the last decade has seen huge advances in *in vivo* neuroimaging technologies. Scientists are now able to study the workings of the human mind in healthy participants as they solve problems and perform other sorts of cognitive and emotional tasks in real time. Availability of these new-research technologies is pushing the field forward at an unprecedented pace; hardly a week goes by, it seems, without a picture of the brain appearing on the cover of a major magazine or in a major newspaper article.

To make sense of the new findings, it is critical that educators understand the logic and constraints in the neuroscience research underlying these articles. While neuroimaging techniques differ in their specifics, there are three main approaches. The first approach involves measuring and localizing changes in the flow of blood in the brain as subjects think in different ways, under the assumption that changes in regional blood flow are indicative of changes in neural activity. The second approach involves measuring the electrical activity of the brain, generated by the firing of networks of neurons (brain cells). The third approach involves measuring changes in the anatomy and structure of the brain. In conjunction or separately, these techniques can be used to study the neurological correlates of a wide variety of tasks, such as reading, math, or social processing, as well as developmental changes (for reviews, see Katzir and Pare-Blagoev, 2006; Thatcher *et al.*, in press).

While these recent advances in neuroimaging have had a profound effect on the field of neuroscience and its potential relevance to education, it is important to remember that new technological capabilities inevitably come with limitations. For example, in functional magnetic resonance imaging (fMRI), the changes in regional blood flow in the brain associated with a particular task of interest are not absolute, but either implicitly or explicitly calculated from comparisons between a target and a control task. The design of the two tasks and the differences between them are critical to the findings and interpretation. When one brain area is reported to light up (i.e., to become more active) for a particular task, this does not mean that the lighted brain area is the only area actively processing. Instead, this means that this particular area was relatively more active for this task than for the control task. Many other areas are certainly actively involved, but are equivalently active in the two conditions. In reality, a network of neural areas always supports the skill being tested. As educators are concerned with supporting the development of coherent functional skills rather than isolated brain areas, it is essential that neuroimaging findings be correctly interpreted before any attempt can be made to apply them in the classroom.

Educational Skills are Supported by Specialized Neural Networks

Nonetheless, the advent of neuroimaging has precipitated major advances in neuroscientists' understanding of how the brain works. In the past, the neuroscientific localization tradition prevailed; that is, cognitive functions were mapped onto specific locations in the brain, as much as possible in one-to-one correspondence. However, neuroscientists now understand that learning involves the development of connections between networks of brain areas, spread across many regions of the brain. This means that while specific brain areas do carry out characteristic kinds of processing, skills for real-world and academic tasks are embodied in the networks they recruit, rather than in any one area of the brain. For example, there is no music, reading, or math area of the brain that is not also involved in processing many other skills and domains (culturally constructed areas of knowledge).

Instead of one brain area, learning involves actively constructing neural networks that functionally connect many brain areas. Due to the constructive nature of this process, different learners' networks may differ, in accordance with the person's neuropsychological strengths and predispositions, and with the cultural, physical, and social context in which the skills are built (Immordino-Yang, 2008). There are various routes to effective skill development, for example, in reading (Fischer *et al.*, 2007) or math (Singer, 2007). The job of education is to provide support for children with different neuropsychological profiles to develop effective, yet flexible skills. Children use whatever capacities they have to learn the most important skills in their lives, and although there is often a modal way of learning a specific skill, people can adapt their capacities to learn skills in diverse ways. For example, Knight and Fischer (1992) found that young children followed one of three pathways in learning to read words. In a related vein, in studying two high-functioning adolescent boys who had recovered from the surgical removal of half of their brain, Immordino-Yang (2007) found that each boy had compensated for weaknesses by transforming important neuropsychological skills into new ones that suited the boys' remaining strengths.

Neural Networks for Mathematics

One area that has seen much advance in the past few years is the study of neurological networks underlying processing for mathematics and number representation. Overall, the findings suggest that networks for processing in math are built from networks for the representation of quantity that start in infancy – one for the approximate representation of numerosity (numeric quantity), and one for exact calculation using numbers (Dehaene *et al.*, 2004). These networks are further organized and differentiated with development and training in math concepts (Singer, 2007). For example, preschoolers go beyond innate number systems to build a mental number line, gradually adding one digit at a time (Le Corre *et al.*, 2006).

Interestingly, this math network shares many processing areas and features with language processing, including reading. Current research is exploring how math processing relates to other domains, such as spatial representation, as well as the development of math networks in atypically developing populations, such as children with learning disabilities.

Neural Networks for Reading

Another area of concentrated research interest is the study of reading development, both in typically developing and dyslexic children. Acquiring literacy skills impacts the functional organization of the brain, differentially recruiting networks for language, visual, and sound representation in both hemispheres, as well as increasing the amount of white-matter tissue connecting brain areas. Work on individual differences in the cognitive paths to reading has enriched the interpretation of the neurological research (e.g., Knight and Fischer, 1992), and helped to bridge the gap between the neuroscience findings and classroom practice (Katzir and Pare-Blagoev, 2006; Wolf and O'Brien, 2006). In dyslexic readers, progress is being made toward better understanding of the contributions of rapid phonological processing (Gaab *et al.*, 2007), orthographic processing (Bitan *et al.*, 2007), and visual processing to reading behaviors, as well as to thinking in other domains (Boets *et al.*, 2008). For example, the visual field of dyslexics may show more sensitivity in the periphery and less in the fovea compared to nondyslexics, leading to special talents in some dyslexics for diffuse-pattern recognition (Schneps *et al.*, 2007). Most recently, research looking at developmental differences in neurological networks for reading across cultures has begun to appear (e.g., Cao *et al.*, 2009), which ultimately may contribute to knowledge about how different kinds of reading experiences shape the brain.

The neural networks for learning reading and math have important implications for education, as the most effective lessons implicitly scaffold the development of brain systems responsible for the various component skills. For example, successful math curricula help students to connect skills for calculation with those for the representation of quantity, through scaffolding the development of mental structures like the number line (Carey and Sarnecka, 2006; Griffin, 2004; Le Corre *et al.*, 2006). While different students will show different propensities for the component skills, all students will ultimately need to functionally connect the brain systems for quantity and calculation to be successful in math.

Domain-General and Emotion-Related Processes Enable Learning

The brain is a dynamic, plastic, experience-dependent, social, and affective organ. Due to this, the centuries-long debate over nature versus nurture is an unproductive and overly dichotomous approach to understanding the complexities of the dynamic interdependencies between biology and culture in development. New evidence highlights how humans are fundamentally social and symbolic beings (Herrmann *et al.*, 2007), and just as certain aspects of our biology, including our genetics and our brains, shape our social, emotional, and cognitive propensities, many aspects of our biology, including processes as fundamental as body growth, depend on adequate social, emotional, and cognitive nurturance. Learning is social, emotional, and shaped by culture!

For a stark example of this interdependence between biology, social interaction, and cognitive stimulation, in their work with Romanian orphans, Nelson *et al.* (2007) found that cognitive, social, and physical growth were delayed in institutionalized children, relative to their peers raised in foster or biological families. Although the institutionalized children's basic physical needs were met, the lack of high-quality social interaction and cognitive stimulation lead these children not to thrive.

Overall, while educators often focus on neural networks for domain-specific skills like reading and math, domain-general and emotion-related networks function as modulators and facilitators of memory and domain-specific learning. These networks include emotion, social processing, and attention.

Emotion and Social Processing

One cutting-edge area of research in neuroscience is the study of affective and social processing. All good teachers know that the way students feel, including their emotional states (e.g., stressed vs. relaxed, depressed vs. enthusiastic) and the state of their bodies (e.g., whether they are sick or well, whether they have slept enough, or whether they have eaten), are critical factors affecting learning. In addition, it is now becoming increasingly evident that emotion plays a fundamental role not only in background processes like motivation for learning, but in moment-to-moment problem solving and decision making as well (Adolphs and Damasio, 2000; Haidt, 2001). That is, emotion forms the rudder that steers learners' thinking, in effect helping them to call up information and memories that are relevant to the topic or problem at hand. For example, as a student solves a math problem, she is emotionally evaluating whether each cognitive step is likely to bring her closer to a useful solution, or whether it seems to be leading her astray.

From a neurobiological perspective, emotional processing in the brain depends on somatosensory systems – the systems in the brain responsible for sensing the state of the viscera and body. These systems can reflect actual changes to the state of the body during emotions (i.e., increased heart rate during fearful states, or a feeling of having been kicked in the stomach when hearing bad news), or they can reflect simulated body states, conjuring how the viscera and body would feel, without actually imposing those physiological changes onto the body (see Figure 1 from Immordino-Yang and Damasio, 2007). Through regulating and inciting attention, motivation, and evaluation of simulated or actual outcomes, emotion serves to modulate the recruitment of neural networks for domain-specific skills, for example, for math or reading. In this way, cognition and emotion in the brain are two sides of the same coin, and most of the thought processes that educators care about, including memory, learning, and creativity among others, critically involve both cognitive and emotional aspects (**Figure 1**).

In addition, social processing in the brain is strongly interrelated with the processing of emotion. People's behavior is organized and influenced by cultural factors and the social context, which in turn reflect experience and learning. For example, many of the reasons the student above solves her math problem relate to the emotional aspects of her social relationships and cultural goals – the way her parents will feel about her behavior, or her desire to go to college. In turn, she feels the influences of these cultural constructs as emotional reactions that play out in her body and mind, and predispose her to think in particular ways.

But how does this student internalize or predict the emotional reactions of her parents? Interestingly, research over the past decade has revealed glimmers of the workings of a basic biological system for internalizing the actions, emotions, and goals of others, in order to learn from, empathize with, and influence others in social contexts (Immordino-Yang, 2008; Oberman *et al.*, 2007). Specifically, it appears that watching other people's actions and inferring their emotions and implicit goals recruits some of the same neural systems involved in planning and carrying out those actions in one's own self. This discovery was dubbed as mirroring by its discoverers (Gallese *et al.*, 1996; Umiltà *et al.*, 2001), and while neural systems for mirroring do not tell the whole story of the neurological system for social learning, current research suggests that they afford an important low-level mechanism on which social and cultural learning can build.

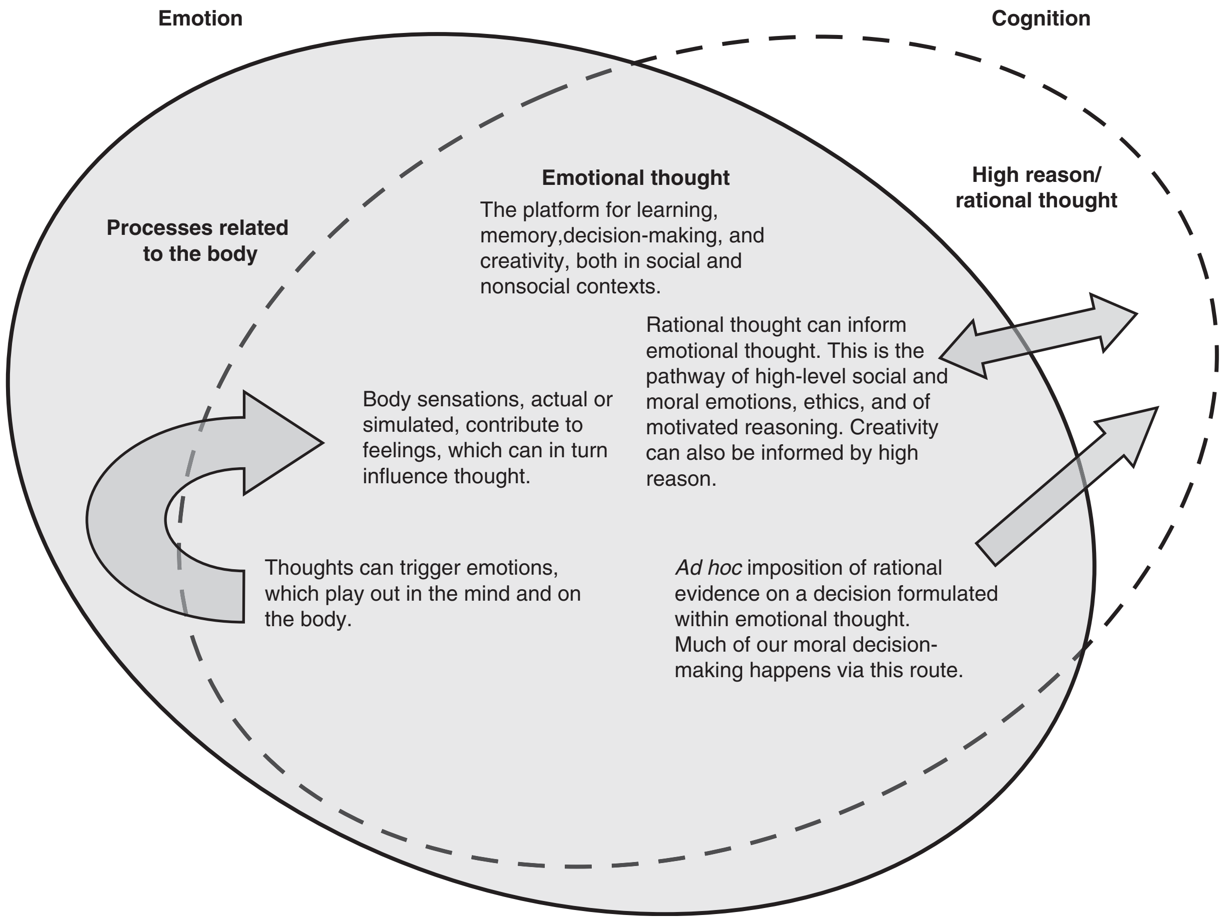

Figure 1 Emotion and cognition come together to produce the thought processes that educators care about, among them learning and memory. In the figure, the solid ellipse represents emotion and the dashed ellipse represents cognition. The extensive overlap between the two ellipses represents the domain of emotional thought. Note that emotional thought reflects a dynamic relationship between the brain and body. Reprinted from Immordino-Yang, M. H. and Damasio, A. R. (2007). We feel, therefore we learn: The relevance of affective and social neuroscience to education. *Mind, Brain and Education* **1**(1), 3–10, with permission from Blackwell publishing.

Memory and Attention

To understand the current state of research on memory and attention, it is helpful to first discuss current views on how reality is constructed in the mind and brain, and the relationship of this process to perception. Work in various areas of neuroscience, for example, in vision or somatosensory perception and location of the body in space, has shown that unlike the often predominant intuitive view, we humans do not construct reality directly from our perception of the environment, as if we were equipped with some sort of internal video camera. Instead, our prior learning, our neuropsychological predispositions, and the current context heavily influence the reality that we construct and experience. That is, reality is never perceived directly from the environment. Instead, we construct reality based on our own best guesses, interpretations, and expectations. For a trite but illustrative example, imagine why visual illusions work: our visual system uses context and prior experience with the world to construct images that incorporate our best guesses about the color, form, movement, and identity of what is actually in front of our eyes.

Related to this, our memories do not reflect the objective replaying of an actual occurrence, but our iterative mental reconstruction of an event, fact, or procedure, for example, the skills to solve a math problem, or a student's conversation with her teacher about her test grade. This means that the iterative reconstruction or mental conjuring of a remembered event will be very similar to the neural processes for imagining an event that never happened, or for simulating possible outcomes of future events. Notably, each of these processes is organized by our emotions, and reflects the subjective meaningfulness and relevance of the remembered, imagined, or simulated thought, as well as the social, physical, biological, and developmental contexts in which the person is operating.

Given all these factors, it is no wonder that different teachers and learners perceive, experience, and remember lessons and educational contexts in different ways!

Another process that is related to the study of memory and emotion, and that is an important prerequisite for the recruitment of neural networks, is attention. The last decade marks theoretical and methodological advances in the study of attention and its relationship to the development of academic skills (Corbetta and Shulman, 2002). In particular, Posner and colleagues have distinguished three different attentional networks important for learning, including networks for alerting, orienting, and executive attention (for a review, see Posner and Rothbart, 2007). They have also shown that individual differences in attention networks can be related to genetic and environmental factors, and that training in these aspects of outwardly directed attention, that is, the ability to regulate one's focus on different aspects of the environmental context, can improve preschooler's academic abilities in various areas such as reading skills and social interaction at school (Berger *et al.*, 2007). Future work should investigate how attention monitoring can be taught in schools, as a way to increase the efficiency with which neural networks are built and recruited.

Back to the Big Picture: Mind, Brain, and Education are Becoming Usefully Connected

Over a decade ago, John Bruer cautioned educators that given the current state of knowledge, directly connecting brain science and education was premature – a bridge too far (Bruer, 1997). But, much has happened since then to narrow the chasm between these two sources of knowledge about development and learning. A new field has been established whose aim is to further knowledge about children's learning by bringing together methods and evidence from various fields, among them neuroscience, psychology, cognitive science, and education.

In this stimulating climate, it is important that new neuroscience advances be carefully examined in light of psychological, developmental, and pedagogical theory and research, to ensure that the field proceeds with caution as well as optimism toward educational innovation. In the past, techniques and ideas from so-called brain-based education have led to the formation of neuromyths – oversimplified, misunderstood, or misapplied notions whose integration into educational contexts is unjustified and, in some cases, detrimental or even dangerous. Instead, findings from neuroscience must be carefully implemented and evaluated, starting in educational microcosms such as research schools, where students and faculty partner with cognitive neuroscientists in the design and assessment of research.

In conclusion, it is an exciting time for the field of MBE, and for studying the neuroscientific bases of learning. In the end, learning happens primarily in the brain; studying the neuroscientific bases of learning can therefore provide educationally relevant insights that, with careful implementation and evaluation, may improve schools and other learning environments for the generations to come.

See also: Attention in Cognition and Early Learning; Knowledge Domains and Domain Learning; The Neuroscience of Aging and Cognition; The Neuroscience of Reading.

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http://faculty.washington.edu – UW Faculty, Neuroscience for Kids.