Mind, Brain, and Education: Building a Scientific Groundwork for Learning and Teaching[1]

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ABSTRACT—The primary goal of the emerging field of Mind, Brain, and Education is to join biology, cognitive science, development, and education in order to create a sound grounding of education in research. The growing, worldwide movement needs to avoid the myths and distortions of popular conceptions of brain and genetics and build on the best integration of research with practice, creating a strong infrastructure that joins scientists with educators to study effective learning and teaching in educational settings. Science and practice together provide many potentially powerful tools to improve education. Neuroscience and genetics make possible analysis of the "black box" of biological processes that underpin learning. Understanding the biology of abilities and disabilities helps educators and parents to facilitate individual students' learning and development. Cognitive science provides analyses of the mental models/metaphors that pervade meaning making in human cultures, creating tools for avoiding unconscious distortions and crafting effective educational tools. Developmental and learning science produce tools to analyze learning pathways, including both shared patterns and learning differences. To reach the potential of grounding education effectively in research requires improving the infrastructure by creating (a) research schools where practice and science jointly shape educational research, (b) shared databases on learning and development, and (c) a new profession of educational engineers or translators to facilitate connecting research with practice and policy.

The emerging field of Mind, Brain, and Education (MBE) aims to bring together biology, cognitive science, development, and education to create a strong research foundation for education. This foundation requires a new approach to connecting research and education, with a two-way collaboration in which practitioners and researchers work together to formulate research questions and methods so that they can be connected to practice and policy. The traditional model will not work. It is not enough for researchers to collect data in schools and make those data and the resulting research papers available to educators. That is not a way for research to create knowledge that is useful for shaping education. The traditional way leaves out teachers and learners as vital contributors to formulating research methods and questions. Contributions from teachers and learners can create more useful research evidence that can feed back productively to shape schools and other learning situations.

There are many cases in the modern world where science and practice together shape research questions, leading to usable knowledge. Consider the field of medicine, where biologists and medical practitioners (physicians, nurses, etc.) work together in teaching hospitals and other locations of practice to connect research to issues of health and illness. In medicine, research and practice are thoroughly intertwined, resulting in huge improvements in treatments and interventions. More generally, research and practice combine routinely in many industries and fields (Hinton & Fischer, 2008). Meteorology combines science and practice to analyze and predict weather patterns (e.g., National Center for Atmospheric Research, http://www.ncar.ucar.edu/research/meteorology/). Cosmetics companies spend billions doing research on skin care, makeup, and personal hygiene, producing thousands of products grounded strongly in research evidence. Food processing, automobile manufacturing, agriculture, the chemicals industry, construction—almost every major modern business grounds itself solidly in research that is shaped by practical questions about how products function and how they can be used effectively in context.

What happened to education? If research produces useful knowledge for most of the industries and businesses of the world, then shouldn't it be serving the same function for education? Somehow education has been mostly exempt

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from this grounding in research. Dewey (1896) proposed the establishment of laboratory schools to ground education in research through combining research with practice in schools, ensuring both formative evaluation and democratic feedback. Unfortunately, his vision has never been realized. There is no infrastructure in education that routinely studies learning and teaching to assess effectiveness. If Revlon and Toyota can spend millions on research to create better products, how can schools continue to use alleged "best practices" without collecting evidence about what really works?

This lack of grounding in research is a key reason that governments in many parts of the world have begun to assess learning in schools through standardized testing in projects such as Program for International Student Assessment (Organization for Economic Cooperation and Development [OECD], 2007a) and No Child Left Behind. The narrowness of these assessment tools creates serious problems, however, for determining the effectiveness of learning and teaching; and, it mostly precludes input from teachers and learners into the assessment process. Could Toyota determine how its cars performed by testing them on a racetrack and ignoring what they do in everyday driving situations? Could Revlon or Avon create effective cosmetics by testing effects only for people gathered into large meeting halls once a year? What education needs is assessments of real school performances that are shaped by researchers, teachers, and students working together to examine the effectiveness of many aspects of learning and teaching in the context of schools (curricula, school arrangements, classroom types, etc.)—what Daniel and Poole (2009) call pedagogical ecology.

THE MBE MOVEMENT

In the past few years of the 20th century something bubbled up almost simultaneously in Paris; Tokyo; and Cambridge, Massachusetts—an interest in bringing biology and cognitive science into close relationship with education, to foster deeper knowledge of learning and teaching. In Paris, Bruno della Chiesa and others created the project on Learning Sciences and Brain Research at the Council on Educational Research and Innovation of the OECD. They brought together scientists and educators to create relationships to foster educational research and eventually published two books about learning science and the brain (OECD, 2002, 2007b). In Tokyo, Hideaki Koizumi and others launched a movement to connect biology with education, eventually creating the Baby Science Society of Japan and launching a series of major longitudinal studies of learning and development in Japanese children (Koizumi, 2004). In Cambridge, Kurt Fischer, Howard Gardner, and others started a training program for graduate students interested in connecting biology, cognitive science, and education, which was named MBE, building on the foundation of the Mind, Brain, and Behavior Interfaculty Initiative that had started at Harvard a few years earlier (Blake & Gardner, 2007; Fischer, 2004). At the same time, Anne Rosenfeld, Kenneth Kosik, and Kelly Williams began the series of conferences on Learning and the Brain (mostly in Cambridge) to educate teachers about neuroscience and genetics as they relate to educational issues (http://www.edupr.com/).

Within a few years, the groups from Cambridge, Tokyo, and Paris began to collaborate, founded the International MBE Society, and launched the journal *Mind, Brain, and Education*. This joint effort was greatly facilitated by the Pontifical Academy of Sciences in Rome, which for its 400th anniversary celebration in 2003 asked the MBE program at Harvard, with the leadership of Antonio Battro of Argentina, to organize 2 days of meetings about research on MBE around the world. From these beginnings, a number of other meetings, books, and projects have been launched, with new ones appearing ever more frequently. For example, there are now established programs to train educators and researchers to relate biology and education at the University of Cambridge (Goswami, 2006), Dartmouth University (Coch, Michlovitz, Ansari, & Baird, in press), the University of Texas at Arlington (Schwartz & Gerlach, in press), the University of Southern California (Immordino-Yang, 2007), Beijing Normal University, and Southeast University in Nanjing, as well as the original MBE program at Harvard and continuing activities in Tokyo and Paris.

Along with all these efforts to shape research, practice, and policy has come a near obsession in the press and on the Internet with neuroscience, genetics, and education, as well as often irresponsible efforts to sell many commercial projects with claims that they are "brain based." Expectations for neuroscience and genetics to shape educational practice and policy have exploded far beyond what is merited by the state of the emerging field of MBE and the level of knowledge about how brains and genetics function (Fischer et al., 2007; Fischer, Immordino-Yang, & Waber, 2007; Goswami, 2006; Hinton, Miyamoto, & della Chiesa, 2008; Katzir & Paré-Blagoev, 2006; Stern, 2005). Many "neuromyths" have entered popular discourse—beliefs about how the brain and body work that are widely accepted but blatantly wrong (OECD, 2007b). Most of what is put forward as "brain-based education" builds on these scientifically inaccurate myths: The one small way that neuroscience relates to most brain-based education is that the students have brains. There is no grounding for these claims in the young field of neuroscience.

This unfortunate situation requires that we build with (a) a strongly skeptical approach to brain-based claims and that we move toward (b) systematic collaborative work that relates biological and psychological knowledge to education and that connects teachers and students with researchers, and

(c) long-term improvement of the infrastructure for creating scientific knowledge that relates to education. If the field can move in these directions, then we can begin to use research tools, such as brain imaging, analysis of cognitive processing and learning, and genetics assessment to illuminate the "black box" and uncover underlying learning mechanisms and causal relations (Hinton & Fischer, 2008).

COGNITIVE MODELS (METAPHORS): BASES FOR NEUROMYTHS AND POTENTIAL FOR EDUCATIONAL IMPROVEMENT

In language and culture, human beings employ key models for understanding and analysis that provide basic concepts and principles for perceiving and thinking in certain ways. This argument has been elaborated extensively by anthropologists and other scholars for many decades (Benedict, 1934; Levi-Strauss, 1966). Recently, cognitive scientists have created tools for analyzing the nature and content of the models behind human understanding, and their analyses illuminate how these biases sometimes support myths about learning and the brain. For example, Lakoff and Johnson (1980) lay out the framework for analyzing these (mostly unconscious) models through linguistic analysis, and Vidal (2007) portrays the models about the nature and role of the brain that developed in the 20th century.

Brainhood and Conduit Metaphors

The modern model of the human mind puts the brain as the core organ that carries most of consciousness and learning—what Vidal calls *brainhood*, the brain as the source of personhood and self. In a dominant and simple form, people are mostly equated with their brains, as if a person could be a brain in a bucket or a laboratory vat or as if the fundamental nature of a person is contained in his or her brain. A person's body, relationships, and culture are treated as secondary at best. Using this model, people talk as if learning occurs in the brain, leaving out the ways that the body contributes to learning, as well as the roles that a person's environment plays in shaping learning and providing information. When people learn, according to this model, they store knowledge in their brain, and there it sits until they need to recall it, as if the brain is primarily a repository (library, computer memory) for information. In one caricature, we can wake up in the morning, download the information that we need for the day, and process that information as we need it in our work.

In analyzing learning and teaching and what happens in schools, this mythical model joins with another model that appears to be broadly distributed across human cultures and historical periods—the *conduit* model of knowledge transmission (Lakoff & Johnson, 1980; Reddy, 1979). When people learn something, they obtain an object (an idea, concept, or thought), which they then possess. To teach it to someone else, they need simply transmit it, as if through a conduit, giving or pumping the information into the person. They can also place the knowledge object in some other source, such as a book or Web site.

Here are some examples from common conversation that illustrate how people use this metaphor, mostly unconsciously and sometimes for humor. "Christina traded stories with Rose." "Katie discovered an explanation in the book." "Laura gave the idea to David, and he scrambled it up." "Bennett stole the hypothesis from Marshall." "I told you the answer. Why don't you get it?" Individuals can manipulate ideas, concepts, or thoughts too, which are seen as normally inhabiting the mind. "Howard can't get this idea out of his mind." "What do you have in mind?" "Zak lost his idea. It must have fallen out his ear."

According to the conduit model, teachers in schools share these knowledge objects with students, and then the students have the objects. Or at least they are supposed to have them. If the students do not use the objects effectively (understanding the knowledge and manipulating it), then they are judged to be stupid or lazy, or sometimes the teacher is judged to have not transmitted the information effectively. Knowledge is available as information, and students are supposed to take it and use it. Of course, good teachers and students know that learning does not follow this model, but the conduit metaphor is so pervasive in human language and culture that it is hard to escape its influence.

Knowing as Actively Constructing

Wouldn't it be great if learning were so simple? Knowing some topic or skill would involve learning a compendium of facts about it—the location of a good tract of farmland in Minnesota, the month when a crop can be planted there, the depth that seeds need to be planted, the normal rainfall that can be expected, and so forth. Put together a few of these facts, and a farmer knows how to grow food in Minnesota—not! Being a successful farmer requires so much more than a list of facts. It requires using the knowledge in a series of activities over months and years to plan, plant, harvest, and keep learning how to improve growing conditions.

In the same way, cognitive and neuroscience research shows that knowledge is based in activity. When animals and people do things in their worlds, they shape their behavior. Based on brain research, we know that likewise they literally shape the anatomy and physiology of their brains (and bodies). When we actively control our experience, that experience sculpts the way that our brains work, changing neurons, synapses, and brain activity (Hubel & Wiesel, 1970; Singer, 1995). When we are simply exposed to events and information (as opposed to acting on them), our brains and bodies are not much affected.

In the same way, school learning is based in activity. If learning involved simply acquiring knowledge objects, then students would not need to go to school for a dozen or more years to become literate and knowledgeable human beings who can be productive members of 21st-century society. It takes years of learning to become able to read skillfully, to explain the causes of the Iraq war, to write a story about the experience of smelling a flower, and to analyze what happens when you drop a ball off a tower. Each generation needs to build knowledge anew; it cannot be simply given or transmitted (Vygotsky, 1978). Students and teachers must work to understand concepts. Memorizing facts is not enough, especially in the 21st century, where people must constantly adapt their knowledge to the rapidly changing world.

Fortunately, cognitive and neuroscientists have been working for over a century to understand how people create and use knowledge. Learning and teaching require active construction of knowledge, as research has demonstrated consistently in cognitive science for over a century (Baldwin, 1894; Bartlett, 1932; Piaget, 1952) and in neuroscience for 50 years (Singer, 1995). The conduit metaphor works to some degree for learning bits of information, but for using knowledge instead of reciting facts, cognitive and neuroscientists are replacing the conduit metaphor with a model of *knowledge as actively constructed*. People build knowledge by using it actively to do things in the world. For example, Piaget's (1952) fundamental metaphor for knowledge is grasping ideas and facts with the mind and manipulating them physically and mentally. Mathematics illustrates this process directly in its fundamental operations, such as addition and multiplication, where objects are combined and grouped to produce numerical outcomes.

By analyzing the metaphors in human language and culture, we can understand how they shape our thought and action, and we can create models that work more effectively. I will return below to describe ways that metaphors can be used to facilitate teaching and learning in schools.

CONSTRUCTIVE BRIDGING: ORGANIC FOUNDATIONS OF ACTIVITY AND LEARNING PATHWAYS

From early in the young history of the MBE movement, some researchers have expressed severe skepticism about the usefulness of linking biology, especially brain science, to education (Bruer, 1997; Hirsch-Pasek & Bruer, 2007). The core argument is that going from biology to education is "a bridge too far" because it is not possible conceptually or practically to connect biological knowledge directly to analysis of school-related learning. Instead, the best that can be done is to use cognitive science as an intermediary, going from neuroscience to cognitive science, and then in turn from cognitive science to education. According to this argument, education is thus firmly separated from neuroscience. The argument is faulty because it is based on a narrow metaphor and a limited set of examples that omit the broad usefulness of biological analysis in promoting educational goals.

Bruer (1997) uses the work of Case and Griffin (Case & Griffin, 1990; Griffin & Case, 1997) on early mathematics learning to support his argument. Research on brain processes in arithmetic, such as Dehaene's (1997), can be related to analysis of the cognitive processes of arithmetic. Then, in turn the cognitive processes can be related to educational practices, such as teaching students to use the number line in arithmetic tasks. But going directly from the brain research to the educational practice is a bridge too far. Case and Griffin analyzed how children construct understanding of the number line, which serves as a foundation for arithmetic, and showed how curricular materials and games can be used to promote and speed up that learning and to create more effective generalization of the number-line model.

At the present time, it is indeed difficult to move directly from Dehaene's analysis of number systems in the brain to mathematics curriculum, but this example and the few others described by Bruer do not prove the general point. The bridge-too-far analysis neglects consideration of the usefulness of bringing biological concepts into thinking about many educational situations. Often, understanding the biological (organic) foundations of activities and learning pathways greatly facilitates educational objectives and at the same time illuminates neuroscientific questions.

Learning With Half-Brain Children

Research on half-brain children provides an illuminating example of both the importance of biological information for facilitating educational objectives and the usefulness of educational outcomes in illuminating neuroscientific questions (Battro, 2000; Immordino-Yang, 2007). This lesson applies not only to children with severe, organically based deficits but also to the full range of children, all of whom have variable abilities in diverse domains that are biologically grounded.

With some severe forms of epilepsy, one hemisphere of the brain is the main locus of epilepsy, and it needs to be removed to stop seizures and to prevent damage to the healthier hemisphere. As a result of the hemispherectomy, these people end up with only half a brain. Yet contrary to expectation, some of the half-brain children have grown up in environments that are highly supportive of learning and have developed strong skills—even skills that traditional neuroscience indicates they are not supposed to be capable of.

To provide optimal support for the learning of a hemispherectomized child requires knowledge of the biology of the brain and body, especially of the special problems that are created by losing a hemisphere. For example, a child with no right hemisphere has relatively poor control of the left side of his body, especially his arm and leg, because of the hemiparesis that derives from removal of the right hemisphere. (The right hemisphere exerts more control over the left side of the body, and the left hemisphere exerts more control over the right side.) In contrast, a child with no left hemisphere has poor control of the right side of his body. Information about such biological characteristics of brain and body greatly facilitates supporting children's activity and learning. Without this biological knowledge, caregivers and teachers face greater challenges in helping children to cope with their physical limitations.

Nico had his right hemisphere removed when he was 3 years old to prevent recurring severe epileptic seizures. Based on the neurological literature, his family was told that he would have poor visual-spatial skills, such as drawing, and poor control of language intonation because these skills are believed to be localized in the right hemisphere. Despite this information, Nico's family and schools provided strong support for his development in many areas, including physical activities, drawing, and speech. With the extensive support that he received, he developed good motor skills, such as running skateboarding, and riding a bicycle. Nico was interested in drawing, which his parents and teachers also supported, and remarkably he became skilled at sketching, as shown in Figure 1, his sketch of the guesthouse where he stayed in Cambridge at age 12 during a visit to our laboratory. Now, as a young adult, he is known for his skill as an artist—contrary to the neuroscientific predictions that he would never have good visual-spatial skills.

Perhaps even more impressive is the case of Brooke, who had his left hemisphere removed at age 11 for severe epilepsy. This age is late for such surgery because the brain's ability to recover from such severe intervention and to adapt to needs for new learning generally decreases with age (Bailey, Bruer, Symons, & Lichtman, 2001). Brooke and his family were told that he would never speak again after his hemisphere was removed, and immediately after the operation, he was indeed unable to speak. However, he began to speak some words soon afterward, and over some months, he gradually learned to speak English again, becoming skilled enough at both speech and reading that he could attend a normal school and eventually a community college. This recovery was shocking to doctors and neuroscientists working with Brooke and gratifying to him and his family (of course).

Key for both Nico and Brooke is that their families and teachers worked with them to help them learn to draw and speak, not accepting the prediction that they would never be able to master such skills. Many handicapped children can learn to master skills when they live in environments that strongly support their learning and development. These two

Fig. 1. Drawing of guesthouse in Cambridge by Nico at age 12.

half-brain boys showed a remarkable plasticity in their learning and brain development. Despite having lost an entire hemisphere, they learned what they were not supposed to be capable of. A crucial contribution to their learning was the constant support they received from their families and schools, which included specific aid in mastering skills for drawing and speaking, respectively.

Use of Intonation in Speech

Immordino-Yang (2004, 2007) studied an important language skill in both Nico and Brooke—the use of intonation (sometimes called melody or prosody) to perceive and signal affective meaning in a sentence. For example, with different intonation, the sentence "We won the game" can change from a simple statement of truth (We won the game) to a sarcastic statement signifying a loss (We WON the game) or a question indicating uncertainty about who won (We won the game?). According to neuroscientific research, processing intonation contours is localized mostly in the right hemisphere, which predicts that Nico should be unable to use them because he lacks a right hemisphere, whereas Brooke should be able to use them because he has one. Immordino-Yang's analysis of these speech skills produced surprising results that provide insights into brain plasticity—how people can perform the same skills through different kinds of processes.

Contrary to predictions of poor intonation skills because of removal of his right hemisphere, Nico's spontaneous speech and listening skills seemed to indicate that he used intonation contours appropriately. Immordino-Yang devised a set of tests of reception and production of contoured speech and administered them to Nico and to a number of his Spanish-speaking peers in Argentina. He performed well on the initial tests, outperforming most of his peers, despite his hemispherectomy. With more detailed and differentiated tests, he performed average or better, except when he was asked to integrate intonation differences with contextual meaning of a situation. Nico's strong intonation performance was a major surprise for neuroscience because he has no right hemisphere!

Brooke was given the same tests, administered in his native language of English and compared to a group of English-speaking peers from his community. He too performed in the normal range on most of the tests, and he excelled in analysis of intonation in stories. Like Nico, he had difficulty integrating intonation differences with contextual meaning. Brooke's skills at intonation were perhaps less surprising than Nico's because the right hemisphere is supposed to be the location for intonation-contour skills.

Immordino-Yang followed up these tests with further assessments and more refined analyses to determine how the two boys performed their intonation-contour skills. Did they use the same kinds of processes and strategies to analyze intonation contours or did they use different processes and strategies? She found evidence that they performed the same intonation skills in distinctly different ways, and those differences fit with the characteristic processing patterns of the hemisphere that each of them retained. Nico used grammar-like processing patterns, which are often localized more in the left hemisphere, while Brooke focused on emotional meaning of contours, which is typically localized more in the right.

Nico analyzed contour by using processing patterns like those that are used to mark intonational differences in grammar and lexical meaning, which are typical of the left hemisphere. In English, those include differences between a statement (descending intonation at the end of a sentence) and a question (rising intonation at the end). In Mandarin Chinese (and some other languages), intonation is used to mark meaning, with four different tones (intonation patterns) making four different words and meanings for a sound such as "ma." Nico showed strong skills for discriminating and matching intonations and normal skills for most uses of intonation across situations, but he had difficulty linking intonation with emotion. To explain a judgment based on intonation, such as that a story character was joking in making a statement, Nico typically said "I just heard it" and gave no explanation in terms of the character's perspective or emotional state. He seemed to be using the left-hemisphere system for using intonation to mark grammar-like meaning.

Brooke on the other hand paid special attention to emotion cues in intonation and focused on them in his explanations. The right hemisphere typically responds more to emotions and is more involved in emotion processing than the left. Brooke exaggerated emotion contours in his speech, and in explanations of stories, he directly addressed a person's emotional state and moved from that to inferences about intentions and perspectives in the story. His strategy focused on emotional meaning in intonation rather than use of intonation as a grammatical/lexical marker.

The big message about Nico and Brooke is that, despite their loss of a hemisphere, they functioned well in school and family and became mostly normal in their educational skills, including the acquisition of skills that classical neuroscience indicated they could not learn. Understanding the biological characteristics of hemispherectomy facilitated their learning in family and school, helping parents and educators to support them more effectively. There was no separation of neuroscience from education, no barrier that prevented the use of neuroscientific knowledge to facilitate learning. For learners in general, there is no barrier that keeps neuroscience and other aspects of biology separated from education. The bridge-too-far metaphor and argument are valid only for a few specific neuroscientific arenas where the research evidence cannot yet be helpful in illuminating educational practices and policies. In general, biological knowledge about abilities and disabilities can facilitate both general understanding and specific adaptations to support effective learning.

Different Learning Pathways: Disabilities and Abilities

In the same way that Nico and Brooke learned about intonation in different ways, many learners show different pathways for learning in any domain. Curricula and teacher training often assume that children learn in one way—for example, learning to read according to the standard model by integrating the sounds of words with their meaning and spelling (coordinating sound, meaning, and sight) to create a modal learning pathway. Indeed, when researchers test for learning pathways, they typically find differences (Boscardin, Muthén, Francis, & Baker, 2008; Fischer & Bidell, 2006; Rose & Meyer, 2002). For example, children in Grades 1–3 who were learning to read in public schools in Arizona demonstrated not one but three different learning pathways for decoding common words (Knight & Fischer, 1992). A study of highly successful adults who are dyslexic and struggled to learn to read showed that all of them moved through learning pathways that did not fit the standard, traditional model (Fink, 2006). Assessments of their skills showed also that as adults they continued to struggle with some basic skills such as analyzing word sounds even though they had become accomplished at reading and writing.

In recent decades, research on learning differences has increased in both quantity and sophistication. Besides the high prevalence of different learning patterns, a key finding that some people find surprising is that learning disabilities involve no defect in either genetics or brain characteristics but instead fit the normal distribution of abilities (Petrill & Justice, 2007; Plomin, Kovas, & Haworth, 2007). For example, children and adults with dyslexia have mostly normal skills and no brain anomaly, but they are at the low tail of the normal distribution for certain skills that are important to reading. At the same time, they have other skills that are normal or even show special talent.

These patterns of abilities and disabilities promise to be explained by the patterns of development of brain and skill. Recent evidence indicates that many dyslexic adults have special talents in vision, especially the capacity to integrate information across wide areas of the visual field. They can, for example, detect the contradictions in Escher drawings more easily than nondyslexic adults (von Károlyi, Winner, Gray, & Sherman, 2003). (Escher drawings show a structure that is physically impossible, such as a staircase that appears to go up forever.)

The developmental pathway that leads to this special talent at detecting such contradictions, as well as to difficulty in learning to read, seems to involve a different pattern of development of the retina in the eye and more generally of the visual system (Schneps, Rose, & Fischer, 2007). Most readers have a highly sensitive fovea, the small area at the center of the retinal field where people focus when they read. The fovea has a high density of cone (color) receptor cells, which create the capacity to precisely discriminate parts of a visual pattern, such as a letter *b*. In the typical pattern, in the retina, the density of receptor cells falls off rapidly with distance from the fovea, so that in the periphery, the density of rod (black/white) receptor cells is sparse and that of cone cells is nonexistent.

Some dyslexics have a different pattern. They have a higher density of receptors in the periphery than normal readers, and this density is accompanied by greater skill at integrating visual information in the peripheral field. This difference appears to explain how they can detect anomalies in Escher drawings because they actually detect more peripheral information and integrate it more effectively. In this way, a neuroscientific model of development of the visual system helps explain how some dyslexics develop a distinctive pattern of visual abilities, with less effective foveal skills (such as reading) and more effective peripheral skills (such as integrating visual information across wide areas of the visual field).

ASSESSING LEARNING PATHWAYS AND MAKING USE OF CULTURAL MODELS

Assessing learning pathways in any school domain provides potentially powerful tools for analyzing skills and facilitating learning by taking account of distinctive pathways. Methods have been created in recent years to detect these learning pathways and to use them to connect student learning, curriculum, teaching, and even task and job descriptions (Dawson & Stein, 2008; Fischer & Bidell, 2006). Key to these methods is the discovery of a common scale along which skills develop as people master a domain. This scale provides a universal ruler for mapping learning pathways, which together with related analytic tools creates a way of uncovering and describing learning sequences as well as coordinating them with curriculum, task characteristics, and teaching skills.

Tools for Analyzing Learning In Vivo

Development along the scale involves growth of complexity through differentiation and coordination of components. Reading English text, for example, requires (a) differentiating and coordinating the sounds of words with their meaning and spelling, (b) connecting the words into larger meaning units such as sentences, (c) considering the reader's and writer's goals for understanding and using the text, and much more. Understanding arithmetic operations includes among other things consideration of the relation of addition and multiplication, which are similar but distinct.

As children develop speech, reading, and arithmetic skills, their growth patterns demonstrate a series of spurts in skill like the one in Figure 2 for relating arithmetic operations. In this study, students calculated simple arithmetic problems such as 7 + 7+ 7 and 3 × 7 and then explained how two arithmetic operations related to each other in general and applied those explanations to the particular problems (Fischer,

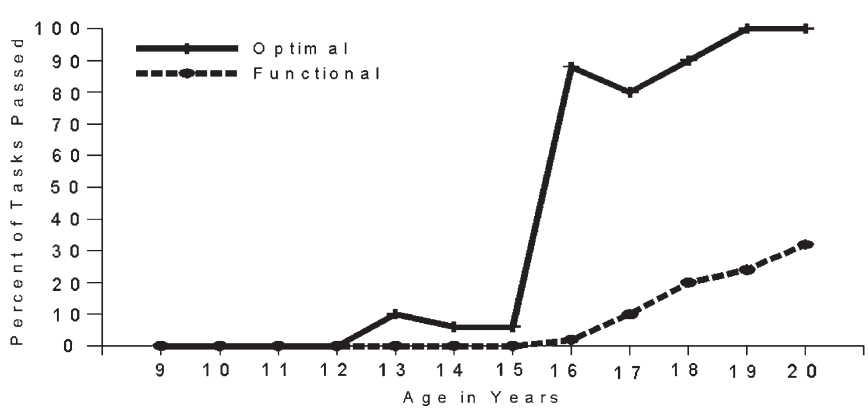

Fig. 2. Spurt in performance for arithmetic mappings under optimal but not functional conditions. Optimal level was assessed with high support and practice (priming with prototype answer plus 2 weeks to think about the concepts), functional level without support or practice (no prototype plus immediate assessment). Reference: Fischer, Kenny, and Pipp (1990).

Table 1

Developmental Scale of Tiers and Levels of Skills

Tiers	Levels	Age of Emergence of Optimal Level	Age of Functional Level
Abstractions	Ab4. Principles	23-25 yrs	30-45 yrs
	Ab3. Systems	18-20	23-40
	Ab2. Mappings	14-16	17-30
	Rp4/Ab1. Single Abstractions	10-12	13-20
Representations	Rp3. Systems	6-7	7-12
	Rp2. Mappings	3½-4½	4-8
	Sm4/Rp1. Single Representations	2	2-5
Actions	Sm3. Systems	11- 13 mos	11- 24 mos
	Sm2. Mappings	7- 8	7-13
	Sm1. Single Actions	3- 4	3-9

Note. Ages for optimal levels are for emergence of the capacity under conditions of support and practice. Ages for functional levels are for ordinary behaviors, which vary widely and are coarse estimates (Fischer & Bidell, 2006). Levels are highly related to education, especially in adulthood (Dawson-Tunik, 2006; Fischer, Yan & Stewart 2003).

Kenny, & Pipp, 1990). The pairs of operations were addition and multiplication, addition and subtraction, multiplication and division, and subtraction and division. Here is one appropriate answer: "Addition and multiplication are similar operations that both involve combining numbers, but addition combines single numbers, while multiplication combines groups of numbers. 7 + 7 + 7 combines three single numbers, while 3 × 7 puts together three groups of seven."

Students in school and university in a midwestern city were assessed in several different conditions, ranging from support and practice for a complex answer to low support and no practice. Ages varied from 9 to 20 years, with equal numbers of boys and girls. Support involved being shown a good answer and explaining it in one's own words. Practice involved performing the tasks once and going home with guiding questions to think about, then returning 2 weeks later to perform the tasks again. When students had both support and practice, performance spurted dramatically between 15 and 16 years; but without support and practice, performance showed slow, gradual improvement, as shown in Figure 2. Optimal performance (with high support and practice) typically shows spurts at specific points in learning and development, whereas functional performance (without support or practice) typically shows slow, continuous growth.

The complexity scale is defined by a series of spurts, drops, and other discontinuities, which mark the emergence of each level of complexity in each skill domain (Fischer & Bidell, 2006). The level in this case is abstract mappings, in which two abstractions are coordinated, such as addition and multiplication or addition and subtraction. Other examples of abstractions that are coordinated as mappings include intention and responsibility, honesty and kindness, or liberal and conservative.

Between birth and 30 years of age, people develop through at least 10 such levels (Table 1), each marked by a cluster of spurts and other discontinuities in optimal performance. These levels begin with actions, which become more complex through a series of levels until they create representations. Then representations in turn become more complex until they create abstractions, which likewise become more

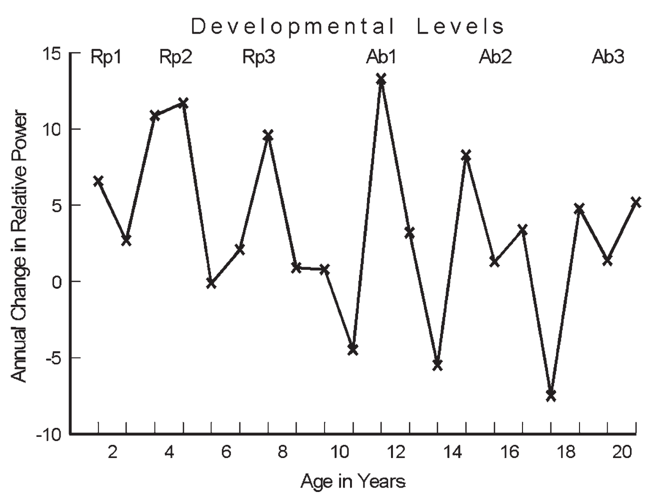

Fig. 3. Spurts in growth of EEG power. Relative power (power in alpha band in occipital–parietal area divided by total power in that area) spurts at regular intervals during childhood and adolescence. The ages of the spurts correlate with those at which major cognitive capacities emerge.

Note. Adapted from Fischer and Rose (1994) based on data from Matousek and Petersén (1973). Rp means representations (1 singles, 2 mappings, 3 systems). Ab means abstractions (1 singles, 2 mappings, 3 systems).

complex at least into early adulthood and create principles for organizing abstractions.

For each skill level, brain activity also reorganizes itself, apparently forming new neural networks to support each skill level. Figure 3 shows how the relative energy in the electroencephalogram (EEG) demonstrates spurts in growth. Evidence indicates that the spurts are correlated with the emergence of new cognitive capacities (Fischer & Rose, 1996). Relative energy is the amount of energy in a part of the EEG (alpha band) divided by the total energy in the EEG for the occipital–parietal region of the cortex.

Research on cognitive development first uncovered this scale for constructing skills and knowledge, but the same scale applies for everyday learning (Dawson & Stein, 2008; Dawson-Tunik, 2006; Fischer & Granott, 1995; Fischer, Yan, & Stewart, 2003). Whenever people learn something new, they move through this scale in building skills in the relevant domain. They even show discontinuities between levels when their responses are scaled using Rasch analysis. In this way, the scale is universal, while at the same time, skills develop independently in each domain or task. For example, understanding how addition relates to multiplication does not affect understanding how intention relates to responsibility.

Understanding the scale and how to use it to analyze learning pathways requires moving beyond the ladder model of development that is built into the English language and replacing it with a model of development as a dynamic web of multiple strands for construction of skills and concepts. Figure 4 shows a constructed web for three independent domains of development—morality, mathematics, and reading. Each domain develops along several strands, marking separate domains that develop mostly independently. Sometimes strands intersect and are coordinated, as when sound and spelling are coordinated or joined for many readers as they learn to read English. Other times, strands differentiate or split, as when addition and multiplication come to be understood as separate operations. Each strand demonstrates development along the same scale shown in Table 1, but the skills in separate strands are mostly independent.

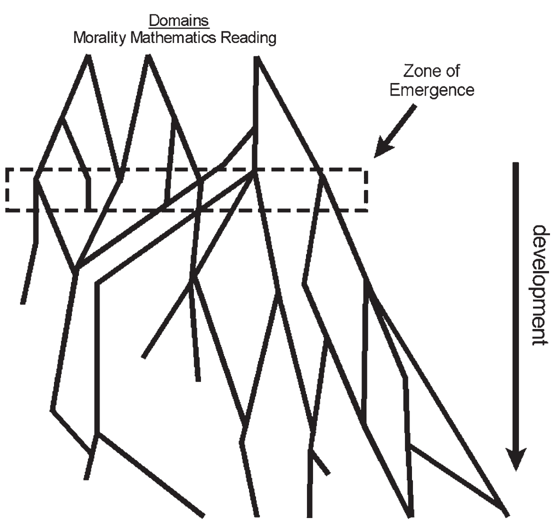

Fig. 4. Constructive web of development. People develop and learn in specific domains, and each domain involves multiple strands of skill. Strands develop mostly independently, and they can join or differentiate. At certain times, discontinuities mark reorganizations and emergence of new capacities, such as the zone of emergence shown.

The emergence of a skill level is marked by a cluster of discontinuities, such as spurts, coordinations, or splits, as shown by the dotted box marked "zone of emergence" in Figure 4. Over the long term, learning and development demonstrate a series of such clustered discontinuities, as can be seen in Figure 4 when looking further down the strands after the marked emergence zone. Thinking about development and learning as involving movement along multiple strands in a constructed web provides a portrait of learning that is much more accurate than the ladder model that is built implicitly into common parlance.

Using Cultural Models to Improve Teaching and Learning

Besides the skill scale and associated tools for analyzing learning pathways, the analysis of everyday metaphors and new ones emerging from research provides potentially powerful tools for improving education. The ladder and web metaphors for learning and development as well as the conduit and activity metaphors for knowledge transmission discussed earlier provide examples. Research on young children's learning of arithmetic provides a powerful demonstration of how a cultural model (metaphor) can be harnessed to quickly and efficiently improve student learning. A metaphor can serve as a conceptual bridge to help children master educationally important concepts and generalize those concepts appropriately (Granott, Fischer, & Parziale, 2002).

Case (1991) proposed that the model of the number line provides a foundation for arithmetic skills in children in preschool and grade school. They studied how they could teach it effectively to young children and found that explicit teaching of the number line had a powerful effect. Especially effective were active games using the number line, such as jumping along a line from 1 to 10 or playing board games that use the number line (e.g., Chutes and Ladders; Griffin & Case, 1997). These effects were particularly strong with children who were educationally disadvantaged and/or initially showed weaker arithmetic skills (Case, Griffin, & Kelly, 2001). The magnitude of the changes from this intervention were unusually large compared to typical educational interventions, with the skill generalizing to many different kinds of arithmetic problems.

This research focused on children in late preschool, kindergarten, and elementary school, and more recent research describes how younger children (about 2–4 years of age) build a number line when they live in an environment that supports learning about number (Le Corre, Van de Walle, Brannon, & Carey, 2006). Young children often learn to recite the elementary digits at an early age—1, 2, 3, 4, 5 . . . That recitation does not mean, however, that they understand the numbers arithmetically. Children were asked to do simple number tasks, such as "Can you give me 1 dinosaur?" or "Can you give me 2 dinosaurs?" or "Can you give me 3 dinosaurs?" Many months were required for them to build up an understanding that each of the elementary numbers represented a specific number of items.

A key aspect of this understanding is called cardinality—that the last number the child counts in a series is the total number in the set of dinosaurs. Children first constructed cardinal understanding for the number 1 at about 27 months, but when they were asked to give 2 items, they did not show cardinality, treating 2 as if it meant more than 1 or many items. Not until 32 months on average did they show cardinality for the number 2, but then they did not demonstrate cardinality for 3 and 4, treating each of them as if they meant many. Gradually over the months, the children added 3 and then 4 as cardinal numbers, and by about 42 months, they established a general understanding of the counting principle, at least for numbers that they could actually count (as opposed to very large numbers): The last number counted in a set specifies the size of the set. In this way, young children gradually construct a number line for the first few numbers in the counting sequence and thus prepare for the kind of instruction that helps children master the general model of the number line for arithmetic, as shown by Case, Griffin, and their colleagues.

The metaphor of the number line is part of everyday discourse about number. Children learn it implicitly when they learn to speak English as well as various other languages. This implicit knowledge of the number line may explain why the effects of number line training were large and relatively fast. If a student already knows a metaphor implicitly, then instruction that brings the metaphor to explicit knowledge can have a rapid, large effect. In contrast, many models/metaphors that are taught in school are difficult, such as the model of conservation of energy in physics or the model of the periodic table in chemistry. Students do not usually learn them quickly.

Metaphors that are part of everyday discourse are strong candidates to use in education when they facilitate learning skills that are targets of instruction. Highlighting these metaphors and creating activities such as games to help students master them may provide opportunities to optimize instruction relatively quickly, as Case, Griffin, and their colleagues have done for early arithmetic teaching. Case (1991) suggested, for example, that the model of a story or narrative is a good candidate for such a teaching target. Teaching based on the model of a story could potentially facilitate learning in, for example, history and literature. In this way and others, metaphors can become a useful tool to facilitate teaching and learning.

CREATING A RESEARCH INFRASTRUCTURE FOR EDUCATION

Clearly, educational research can provide a useful base of knowledge for educational practice and policy. The MBE movement aims to facilitate this process by bringing biology, cognitive science, and human development together with education to create a strong scientific groundwork for teaching and learning. Powerful tools are available to build this groundwork, but the infrastructure is weak for educational research and development. To improve the research foundations of educational practice and policy requires building a stronger infrastructure to create better educational research. That research needs to be not only scientifically sound but also connected with the way teaching and learning happen in important educational settings, such as schools, playing fields, television, and the Internet. Three changes that will contribute to a stronger infrastructure are (a) the creation of research schools to promote research that connects to practice and policy, (b) the establishment of useful databases on learning and development, and (c) the invention of a new class of educator who specializes in translating between research and practice and/or in engineering educational materials and activities based on research.

Research Schools

The MBE movement needs to build institutions that support sustainable collaboration between researchers and teachers in order to create a strong foundation in research for teaching and learning. One of the strongest institutions in medicine for promoting collaboration between researchers and practitioners is the teaching hospital. Researchers and practitioners work together to refine procedures and medications and to generate hypotheses and methods, connecting research and practice and also training future medical researchers and practitioners. Similarly in agriculture, researchers and farmers work together through field tests to improve agricultural products and equipment and to try out different farming methods. Education lacks this kind of infrastructure for creating a scientific groundwork for teaching and learning.

Education and medicine each use a process that is close to the essence of the research enterprise. Experimental research is characterized by a paradigm of intervention followed by assessment. Some condition is created or some change is made, followed by an assessment of what happens as a result. In medicine, the intervention is often a treatment such as medication, inoculation, therapy, or surgery, followed by an assessment of function or health. In schools, teachers regularly try to teach something (an intervention) and then assess the students' understanding or skill, either directly on a test or indirectly through the students' ensuing activity.

Despite this commonality, medicine and education differ greatly in how seriously they treat research in their practice. Every high-quality medical school has at least one teaching hospital, where research and practice are brought together. Yet in education, there are only a few research schools that have research on teaching and learning as a key part of their mission.

Educators need an institution comparable to the teaching hospital—what we call the research school—to connect the work of researchers and practitioners and to craft research methods and questions so that they address important issues in education. Hinton and Fischer (2008) proposed the creation of research schools in a recent issue of *Mind, Brain, and Education*. We propose that research schools should be real-life schools (public and private) and should be closely affiliated with a university and in most cases with a school of education at that university. They should have educators and researchers working together both to create research that illuminates educational practice and policy and to train future researchers and practitioners. We also sketch some recent efforts to create a research school that connects research and practice.

A number of educators and researchers responded to this article with their own contributions to the discussion, which are included in the current issue. Several articles describe in detail other recent efforts to build connections between research and practice in schools and in education more generally (Coch et al., 2009; Daniel & Poole, 2009; della Chiesa, Christoph, & Hinton, 2009; Kuriloff, Richert, Stoudt, & Ravitch, 2009). An article on transdisciplinarity in the field of MBE also discusses ways of putting research and practice together, including research schools (Samuels, 2009).

Research schools build on the ideas of Dewey (1896), who over a century ago proposed the creation of what came to be called "laboratory schools," which were designed to serve this function. The Laboratory School at the University of Chicago, which Dewey (1900) founded, was originally designed to implement practices based on hypotheses from psychology and cognitive science and to field test their effectiveness in vivo—a mission fully consonant with the goals of research schools. Unfortunately, most so-called laboratory schools today have no involvement in research, but instead are elite schools that often provide excellent education but do not serve the function that Dewey originally proposed. We still face the problem that Dewey articulated—the deep inconsistencies between educational practice and research on learning and teaching. We need to establish real research schools as an important institution to create a strong research foundation for educational practice and policy.

Databases on Learning and Development

Another kind of infrastructure that will help provide a strong scientific groundwork for learning and teaching is the creation of large databases about learning and development. The U.S. database for traffic safety, the Fatality Analysis Reporting System, illustrates the potential usefulness of a comprehensive database (Hemenway, 2001). Established in 1966, this system collects systematic data on traffic accidents, especially those involving fatalities, with the result that data are available to determine the safety of many aspects of car design, highway design, and so forth. The effects of this database on traffic safety have been far-reaching and deep, contributing substantially to an enormous reduction in traffic fatalities and injuries over the past 40 years.

A start has been made toward building such databases for education, including the National Assessment of Educational Progress (http://nces.ed.gov/NationsReportCard/); the Child Language Data Exchange System, which assesses language development (MacWhinney, 1996); the National Institute of Child Health and Human Development (NICHD) Child Care project (NICHD Early Child Care Research Network, 1994, 2006); and the state databases for No Child Left Behind. However, these databases include little about how learning and teaching occur in classrooms, in front of computers, or in other learning settings. A database is needed that examines learning and teaching in real-life settings, not just performances on standardized tests in environments that are not part of normal learning in schools or elsewhere. Research schools in collaboration with traditional standardized assessments can move the field beyond ideology and opinion to evidence-based practice and policy.

Creating Educational Translators or Engineers

One goal of the MBE program at Harvard and of the International MBE Society is to produce a new category of educators with skills at making useful connections between research and practice. These educational translators or engineers can help apply findings from cognitive science and neuroscience to learning in classrooms and can engineer educational materials and activities grounded in research that promote learning in educational software, on children's television, or on playgrounds. This role is well established in older sciences, such as physics, chemistry, and biology. The knowledge and models from these mature sciences do not apply directly to practical questions, such as how to build a bridge, how to create a new kind of soap, or how to prevent invasive species from destroying native species in the Great Lakes. In physics, professionals with this kind of expertise are called engineers. Business and government rely fundamentally on engineers in physics and similar specialists at connecting scientific knowledge with practice in chemistry, biology, and other fields.

Education requires such a specialist, perhaps called an education engineer or a neuroeducator (Gardner, 2008).

Research schools would seem a promising institution for training this new kind of specialist. Examples already exist of institutions where professionals work to build connections between research and practice. *Sesame Street* is renowned for the ways that it has used formative evaluation and practical assessments to shape its educational programs (Lesser, 1974). A number of education companies and nonprofit organizations include many individuals with this kind of practical skill, such as the Center for Applied Special Technology (www.cast.org), which creates educational software that facilitates learning and supports diverse learning pathways (Rose & Meyer, 2002).

The International MBE Society welcomes other suggestions about ways to strengthen the infrastructure for creating a scientific groundwork to connect MBE. The potential is enormous, but hope and potential alone will not make it happen. We must create institutions that will generate usable knowledge connecting research with practice and policy, and we must train professionals to create the new world in which research on mind and brain relates directly to practice and policy in education.

CONCLUSION: GROUNDING EDUCATIONAL PRACTICE AND POLICY

The MBE movement aims to create a strong scientific foundation for educational practice and policy by connecting cognitive science, biology, and human development with education and by creating new infrastructural institutions to build strong relations of research with practice and policy. Effective research requires that educators play a central role along with researchers in formulating questions and methods. Biology is central to this emerging field, informing educational practice in many ways through providing basic knowledge about body and brain as they relate to learning and teaching.

Children learn cultural/linguistic models implicitly from an early age, and those models can interfere with application of scientific knowledge to education, creating neuromyths, for example. At the same time, analysis of those models (metaphors) can create opportunities for substantial improvements in education, as has been demonstrated with mathematics teaching in young children.

Cognitive tools provide powerful means for assessing learning pathways with a common scale (ruler), based on analysis of patterns of growth in both long-term development and short-term learning. To build and sustain a strong scientific foundation for education requires creation of at least three new forms of infrastructure: (a) research schools in which researchers and practitioners work together to craft research questions and methods to shape practice and policy; (b) large, shared databases on learning and development; and (c) a new kind of professional who specializes in connecting practical questions with research findings and concepts, an educational engineer.

A strong base in research based on collaboration of researchers and practitioners will lead to many major improvements in education. Evidence will lead to better choices of ways to teach and to facilitate learning, including specification of different learning pathways for different learners. Simultaneously, it will avoid misleading claims of "brain-based education" deriving from myths that are scientifically specious. It will reduce the effects of misleading models of learning and teaching that are implicit in language and culture but not scientifically accurate, while creating ways to teach models more effectively and take advantage of ways that culturally implicit models can improve learning. It will provide new tools for assessing learning pathways, both for teachers and for learners, who will be able to track their own learning in important domains. MBE has an important role to play in improving education in the 21st century.

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