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Summary
The primary goal of the emerging field of educational neuroscience and the broader movement called Mind, Brain, and Education is to join biology with cognitive science, development, and education so as to create a sound grounding of education in research on learning and teaching. To avoid misdirection the growing worldwide movement needs to avoid the many myths and distortions in popular conceptions of brain and genetics and focus on integrating research with practice to create useful evidence that illuminates the brain and genetic bases of learning and teaching as well as social and cultural influences. Scientists and educators need to collaborate to build a strong research foundation for analyzing the “black box” of biological and cognitive processes that underpin learning.

Understanding the diversity of abilities and disabilities will help educators and parents to facilitate individual students’ learning and development. Analyzing the mental models that pervade meaning making in human cultures and the learning pathways along which people develop those models and related skills can provide a strong grounding of education in research. That grounding requires improving the infrastructure for educational research by creating (a) research schools where practice and science jointly shape research, (b) a new generation of interdisciplinary researchers with rigorous training in educational neuroscience, (c) a new profession of educational engineers or translators to facilitate connecting research with practice and policy, and (d) shared data bases on learning and development, including multi-site studies that use common measures across domains.
By Kurt W. Fischer, Usha Goswami, John Geake, and the Panel on the Future of Educational Neuroscience

Educational neuroscience is emerging as a new field that brings together biology, cognitive science, developmental science, and education to investigate brain and genetic bases of learning and teaching. Research and practice combine routinely in many industries and fields to create usable knowledge that has great practical value, but mostly education has not been grounded in such practical research. Creating a strong research foundation for education requires a collaborative approach, with a two-way dialogue 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 and neglects the importance of the ecology of schools and other learning environments. Contributions from researchers, teachers, and learners together can create more useful research evidence that will feed back productively to shape schools and other learning situations (Geake, 2005).

Need for Infrastructure to Ground Learning and Teaching in Research
Both business and government commonly support connecting science and practice in order to create useful outcomes, leading to usable knowledge (Hinton & Fischer, 2008). Meteorology combines science and practice to analyze and predict weather patterns, led by organizations such as the National Center for Atmospheric Research. Cosmetics companies spend billions doing research on skin care, cosmetics, and personal hygiene, producing thousands of products grounded strongly in research evidence. Food processing, automobile manufacturing, agriculture, the chemicals industry, construction....so many fields ground themselves solidly in research that is shaped by practical questions about how products function and how they can be used effectively in real-world contexts.

The field of medicine provides the closest analogy to education, combining scientific research with practice to improve the long-term well-being of human beings. Scientists and practitioners work together in teaching hospitals and other locations of practice to apply research to issues of health and illness. In medicine, which includes the closely related field of public health, research and practice are thoroughly intertwined, resulting in huge improvements in treatments and interventions. For example, identifying predictive risk factors via medical epidemiology can lead to experimental work to identify causal mechanisms for disease, and understanding those mechanisms in turn enables targeted treatments and interventions. The same scientific approach needs to apply to education.

Yet what happened to education? Research produces useful knowledge for most of the industries of the world, yet somehow it does not serve the same function for education (Fischer, 2009; Szücs & Goswami, 2007). Despite the obvious importance of
schools and other learning institutions for the well being of human beings, research on education has been scant, without broad-based institutions to provide means for grounding learning and teaching in research. More than a century ago in 1896 John Dewey proposed the establishment of laboratory schools to provide this grounding by connecting research with practice. Unfortunately his vision has never been realized. There is no infrastructure in education that routinely supports scientific research on learning and teaching to assess effectiveness. If Avon 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? The emerging field of educational neuroscience provides an opportunity to build an infrastructure to create research grounding for learning and teaching, and the National Science Foundation can help facilitate the creation of this infrastructure.

The lack of grounding of education in research is a key reason that governments in many parts of the world have initiated the assessment of students’ learning through standardized testing in programs such as PISA (Program for International Student Assessment) and No Child Left Behind. These assessment tools provide useful data, but they also have serious limitations. They do not assess learning as it takes place in schools and other educational settings but examine only performance on group tests, and they mostly preclude input from teachers and learners into the formulation of research questions and methods. Could General Motors assess cars effectively by testing them on a race track and ignoring what they do in everyday driving situations? Could Revlon create effective cosmetics by testing effects only for people gathered into large meeting halls once a year? Education needs assessments in actual learning situations that are shaped by researchers, teachers, and students working together to examine learning and teaching where learning takes place – what Daniel and Poole (2009) call “pedagogical ecology.”

Obstacles to Moving Forward

Neuroscience and genetics are booming, both scientifically and in the public imagination. This popularity creates problems for educational neuroscience by creating widespread beliefs that are incorrect, and legitimate scientific efforts to rein in expectations lead to problematic overgeneralization of concerns. Scientific findings have been oversimplified to form widely held neuromyths. Simultaneously, legitimate limitations of biological research have been overgeneralized to create barriers to building research that effectively connects biology with education. Of course, there are real limitations to making inferences from neuroscientific evidence, and one area in which caution is required is often called “mind reading,” using brain images to infer mental activity in individual people.

Neuromyths, Ethics, and “Brain-Based Education”

The many scientific advances in neuroscience and genetics have led to a popular obsession that has engendered common neuromyths as well as sometimes irresponsible efforts to sell commercial projects with claims that they are “brain based”. Expectations about how neuroscience and genetics can shape educational practice and policy have grown far beyond what is merited by the state of educational neuroscience
and knowledge about how brains and genetics function (Goswami, 2006; OECD, 2007). Many “neuromyths” have entered popular discourse – beliefs about, for example, right and left brain thinking, male and female brains, how much of the brain people do not use – that are widely accepted but blatantly wrong. 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 students and other learners have brains. These myths typically relate to common mental models that people learn from their language and culture and use unconsciously, such as a model of the brain as a library that stores information and a model of teaching and learning as transmission of information from expert to novice (Lakoff & Johnson, 1980). These implicit models lead to many misconceptions in science, but they can also be harnessed to facilitate education (Fischer, 2009).

The young field of educational neuroscience needs to move beyond these groundless myths and claims and establish a strong research foundation for learning and teaching in educational settings. This foundation must start with insistence on carefully grounded analysis of neural, genetic, cognitive, and emotional components of learning that is based in collaboration of teachers and students with researchers. Most important, for educational neuroscience to reach its potential, infrastructure must be created to catalyze research on learning and teaching, creating scientific knowledge for education. Then research tools such as brain imaging, analysis of cognitive processing and mental models, and genetics assessment can be used to illuminate the “black box” and uncover underlying learning mechanisms and causal relations (Hinton & Fischer, 2008).

An important topic for debate as educational neuroscience emerges is neuroethics, including both the ethics of application of scientific findings to education and the neuroscience of ethics (how ethical behavior is grounded in brain and biology) (Farah & Heberlein, 2007; Illes & Sahakian, in press; Sheridan, Zinchenko, & Gardner, 2005). Many of the materials that are promoted as brain-based in education raise ethical questions because of their inadequate grounding in scientifically sound research. Education has such powerful effects on children that ethical issues should be as central there as they are in medicine. Debate is needed that includes not only the scientific community but also parents and the public.

**Reading Minds from Brain Imaging**

Brain imaging has especially captured the popular imagination, with images of brain anatomy or brain activity appearing regularly in articles in newspapers and on the internet, as well as in scientific papers. Several studies have documented how influential these diagrams are. Readers find articles more convincing when they contain brain images as opposed to graphs or other illustrations (McCabe & Castel, 2008), and neuroscience information is particularly influential in readers who lack relevant background knowledge (Weisberg et al., 2008).

In fact, drawing inferences about mental activity from brain activity is a tricky enterprise, requiring much more careful statistical analysis than is commonly assumed. Most behaviors involve multiple brain regions, not just one or a few, and activity in a brain region or two does not reliably indicate a particular kind of mental operation. For
example, research evidence may show that a brain region such as the rostrolateral prefrontal cortex is active during a particular cognitive process, such as speaking. Activity in this region does not reliably indicate that the person is focusing on a language function, however, because other kinds of processes can also evoke activity in that region. Poldrack (2006) has demonstrated the statistical difficulties of drawing this kind of inference. When inferences connecting brain processes with behavior such as myelination or synaptic pruning are involved, directly relevant data are seldom available, and special caution is required in drawing inferences (Paus, Keshavan, & Giedd, 2008).

**Constructive Bridging: Biological Grounding of Activity and Learning**

Although care is required in drawing conclusions from brain imaging about cognitive and learning processes, biological knowledge in general can be useful in grounding analysis of behavior and learning. From early in the young history of educational neuroscience, skepticism has been expressed about the usefulness of linking biology to education, especially brain science (Briner, 1997). The core argument has been that going from brain science to education is “a bridge too far” because connecting brain knowledge directly to school-related learning is not possible given the current state of the art. Importantly, cognitive science can serve as an intermediary, with a bridge linking neuroscience to cognitive science, and then another bridge in turn linking cognitive science to education. According to this argument education must be combined with neuroscience by cognitive models and analyses. Yet if narrowly framed, the argument can neglect the broad usefulness of a biological framework for analyzing learning and teaching.

Moving from knowledge of the brain such as images of brain activity directly to educational application is indeed difficult in many cases. For example, knowledge of brain regions that play a central role in using mathematics does not obviously facilitate helping students to learn mathematics. But the bridge-too-far analysis omits the usefulness of biological concepts for thinking about educational situations, especially those involving learning differences, including variations in organic capacities. Understanding the biological (organic) foundations of vision or hearing or use of the hands makes important practical contributions to facilitating students’ effective use of their eyes, ears, or hands and thus facilitates educational objectives, while at the same time illuminating neuroscientific questions. Learning differences permeate education, and biological knowledge often illuminates processes involved in those learning differences. The relevance of biology is blatantly obvious when a teacher is dealing with a child who is visually handicapped or has brain damage, and it is often also illuminating in analysis of other kinds of learning differences, ranging from plasticity to limitation in learning and development (Immordino-Yang, 2007; Schneps et al., 2007).

**Diverse Pathways:**

**Many Kinds of Learning, and Many Kinds of Learners**

Learning takes many different forms, varying across brain systems and behaviors within a person and also varying across people and social groups. When schools take on the goal of educating everyone, these differences become vital: Every student has a right to learn effectively, whether they learn easily with traditional instruction or require a
different kind of instructional support. One of the most promising topics for educational neuroscience research is the brain systems necessary for learning and their development.

In order to improve the identification of the particular learning strengths and weaknesses of individual children, an understanding of developmental mechanisms is required. Neuroscience can help provide better understanding of the entire range of commonalities and individual differences, from disability to typical ability to exceptional ability, and neuroscientific and genetic studies support the view that individual differences in learning of any kind follow a normal distribution. For example, most learning difficulties represent the tail end of a normal distribution rather than representing qualitatively different developmental profiles (Kovas et al., 2007). Any understanding of individual differences must also encompass understanding how environmental factors work to amplify or modify learning strengths and weaknesses shown by particular children. For example, identical twins can have markedly different brains, because of epigenetic and environmental factors. Integrating data from cognitive neuroscience with data from anatomical, physiological, and social neuroscience and genetics, within behavioral frameworks from cognitive psychology, can provide a unique means of linking structure and function and thereby understanding the nature of developmental change and the effects of environmental and affective inputs.

Although modern genetics has shown the importance of inherited biological predispositions in shaping individual differences, the environment plays the critical role in determining how these predispositions play out in terms of developmental and learning pathways. Furthermore, epigenetics shows that children create their own learning environments to some extent: Teachers may react to a child’s genotype, and simple behavioral measures will not capture this connection. Likewise, socioeconomic status (SES) appears to have varied effects depending on genetics. For example, for high SES groups genetics shows a stronger link to intelligence test scores because of the relatively uniform environmental experiences of the group. Conversely, for low SES groups, having a genotype that predisposes a student to a learning difficulty plus a sub-optimal environment can act as a “double whammy” in terms of learning outcomes. Providing the optimal educational environments therefore requires a better understanding of the interactions of biology (including brain and genetics) with mind and education. This quest to better understand the biology of learning systems can be informed by neuroscientific accounts of identified learning problems such as dyslexia, dyscalculia, and Asperger’s syndrome.

Three research goals that are feasible for NSF to pursue given the current state of the field are: understanding how the brain and genetics contribute to building structured representations, understanding complexity (of both input and structures of actions and neural systems) via mathematical models that capture this complexity, and creating longitudinal data bases.

1. Understanding the Development of Structured Representations

This goal can be addressed by programs of research that focus on either a particular educational skill (such as literacy, numeracy, reflective judgment, or artistic design) or the development of the representations and processes that mediate people’s
educational interactions (such as language, mathematical symbols, attention, motivation, social interaction, or mental models).

For example, research in the neuroscience of reading and literacy has highlighted the importance of the efficient functioning of various language-related structures (e.g., Niogi & McCandliss, 2006), in particular those linked to phonology (sound structure). Work with atypical readers (deaf readers, children with developmental dyslexia) has suggested a compensatory role for articulatory structures (e.g. left inferior frontal gyrus) when the neural networks that typically support phonological development are inefficient. Hence to foster in all children the optimal development of the structured phonological representations that underpin literacy acquisition, more focus on oral language and articulatory processes may be required. Having developed basic understanding as in this example, research can focus on the roles of other sources of individual differences within this framework (such as social factors, differences in SES, different teaching environments), in order to understand their relative contributions at different points in development. This kind of basic research on mechanisms of individual differences as they relate to learning and education is complementary to categorical disease-based (NIH-style) research approaches, and is necessary in order to account for the large variation that exists across the whole population of learners.

As an example of basic research on the structured representations that mediate all learning (such as those underpinning language or attention), one attainable research goal is to understand the developmental links between precursor skills and how the brain builds expertise. With language, such research aims to investigate learning and development from the very beginning, investigating how the system builds itself up in infancy prior to the emergence of competent language skills. This research requires (for example) understanding the role of basic visual and auditory processing in language development, understanding how small early biases and differences may develop into larger skill differences, mapping the effects of age on learning (does early learning have a "special" role?), and considering all these research questions for educationally critical contexts (such as bilingualism). Within this broad set of goals, such research programs need to include developmental and learning studies that capture interactive specialization – investigations of how changes in one system impact another system. For example, we know that the impact of learning to recognize visual words affects the further development of language systems, but such effects have not been mapped developmentally with respect to which language(s) people are learning or when they are learning them.

2. Understanding Complexity through Models

People naturally build and use mental models, and analysis and manipulation of those models has come to play an essential role in scientific research. Cognitive linguists have analyzed how these models function in human communication and learning (Lakoff & Johnson, 1980). For example, the conduit model of teaching and learning shapes and limits educational practice in many schools and other settings: Teaching is treated as the transmission of information from teacher to learner. In contrast, educators can also make constructive use of mental models by teaching to them explicitly. For example, a mental model that has proved useful for education is the
number line, which is used implicitly in many languages and cultures and can be taught explicitly so that students can learn arithmetic more quickly and effectively (Griffin & Case, 1997). While all people use mental models, scientists use explicit models to characterize their theories rigorously and precisely. Understanding the development of structured representations including both actions and symbolic systems requires explicit modeling of complex systems. Mathematical and connectionist models, such as those derived from engineering, machine learning, and growth modeling, are needed to connect research on cognitive and neural constructs with the effects of learning, individual differences in development and learning, and the nature of developmental change. These models not only capture existing data and help to explain it in principled ways, but they can be important in generating new insights and research questions, such as interpreting different learning systems in interaction with diverse learning environments. To capture many of the characteristics of education, such models will have to be dynamic and nonlinear in structure, explicitly incorporating feedback as a necessary feature of learning.

Model testing will require multivariate analytic methods to deal with the multitude of important factors influencing learning and performance. For example, Bayesian probability models are of increasing importance to understanding neural systems at all levels of neuroscience (molecular, cellular, neural networks). One surprise has been that Bayesian models show that noisy networks improve learning, at both cellular and whole-network levels. Another surprise has been that hierarchical growth models sometimes demonstrate attractors for different skill domains (moving toward the same pattern) while at other times they show dispersion or repulsion between domains.

Insights like these may be critical to advancing a new field like educational neuroscience, as educators are continually faced with “noisy systems” (namely children!). Investigations of how complexity and noise affect learning are already under way in areas of sensory neuroscience, and they may provide models for understanding the development of complex cognitive structures via learning and education. Such investigations in educational neuroscience will need to incorporate measures of learning, in order to study the learning mechanisms themselves, including whether they are intact or impaired.

A core requirement for a systematic understanding of complexity in development is characterization of learning pathways for important educational domains, including detection of differences in pathways for different kinds of learners. Rather than age-normed assessments as with intelligence testing, what is required is assessments that are normed by complexity level as well as brain development, including markers of cognitive variability and diverse learning sequences in populations of children (Fischer & Bidell, 2006).

3. Creation of Longitudinal Databases

Essential for creation of this different kind of assessment is longitudinal studies of large, typically developing populations. One axiom of education is that children develop at different rates and along different pathways, and that better understanding of how these differences occur will facilitate delivery of the individualized instructional programs
that are likely to have the largest pay-off. Because variability in rates and patterns of
development is determined by both biologically based and environmental factors, the
field of education would benefit immensely from a large database of information about
the typically developing brain in its typical environments with respect to population
variability. This information will also facilitate conceptualizing educational inputs in terms
of response to instruction by a student (and brain) at a certain developmental level
(rather than assuming that some lack of inherent ability in a child of a given age).

In order to address the larger research questions concerning complexity of inputs
and structures, it needs to be recognized that learning states and characteristics
(including those in the brain) can be treated as outcome measures that can be applied
at a population level. Longitudinal and intervention studies are most likely to illuminate
underlying causation if they focus around questions such as the following:
(a) How do the brain’s multiple learning systems, each of which operate via different
rules, contribute to learning successes and difficulties in education? What kinds of
models of processes and pathways can usefully represent these learning systems and
their patterns of change over time?
(b) What are the best methods and models to characterize developmental and learning
pathways in order to guide teaching and learning and clarify the relation of learning
difficulties and strengths?
(c) How can researchers and educators identify early neural and biomarkers that
indicate variations in learning patterns and enable early detection of learning difficulties
or strengths?
(d) How can educators use educational environments to optimize trade-offs between
learning and teaching strategies for individual children, such as the mix of rote versus
concept-focused learning?
(e) How are interventions more or less effective when they focus on weaknesses,
strengths, or both, and how does their effectiveness vary across areas of education and
cognition?

How NSF Can Facilitate Educational Neuroscience:
Creating Infrastructure for Education

Educational neuroscience research can both advance scientific knowledge about
the brain and learning and also provide a useful base of knowledge for educational
practice and policy. Although powerful tools are available to build this base, the
infrastructure for educational neuroscience is weak. Improving the research foundations
of educational practice and policy requires creating a stronger infrastructure for
educational research. That research needs to be scientifically sound, but for it to be
useful for education it also must be connected with the ways teaching and learning
happen in real educational settings, such as schools, playing fields, the internet, and
television.

Importantly, the benefits of educational neuroscience for practice and policy can
only be realized if education practitioners, particularly school teachers but also
curriculum designers and educational policy makers, incorporate educational
neuroscientific implications and applications into their professional practices and
policies. To this end, educational neuroscience needs to include an action research
framework in which the genesis and rationale of research arises from educational concerns and the potential applications of the research are field tested in educational settings. Creating this strong connection between research and practice in educational neuroscience requires building new kinds of infrastructure to nurture and sustain the field.

Four essential components of a stronger infrastructure are (1) creation of Research Schools where researchers and practitioners work together, (2) training of a new generation of interdisciplinary researchers expert in both educational and scientific research methods, who can grow the new field, (3) invention of a new category of educational engineers who specialize in translating between research and practice and/or in engineering educational materials and activities based on research, and (4) establishment of useful data bases on learning and development, crafted carefully for improvement of knowledge about educational neuroscience.

Research Schools

Educational neuroscience requires institutions that support sustainable collaboration between researchers and teachers so as to build better research and training on teaching and learning. We propose the creation of Research Schools as a vehicle to improve educational neuroscience research by building institutions that connect researchers with practitioners in order to shape research questions and methods. One of the strongest institutions in medicine for promoting medically usable knowledge is the teaching hospital. There researchers and practitioners work together to both shape research and train future medical researchers and practitioners. The result is not only refining procedures and medications but also generating hypotheses and methods that shape research so that it can more directly affect practice and policy. Similarly in agriculture (and many other fields, such as cosmetics and meteorology) researchers and farmers collaborate in field tests to evaluate and improve agricultural products, equipment, and farming methods. Education lacks this kind of infrastructure for creation of a scientific groundwork for learning and teaching.

Ironically education shares with medicine a paradigm that captures the essence of experimental research – intervention followed by assessment. In an experiment some condition is created or some manipulation is done, and it is followed by assessment of the result. For medicine the intervention is a medication, inoculation, therapy, surgery, or other treatment, which is followed by an appraisal or assessment of function or health. Similarly in schools teachers intervene by attempting to teach something, and they then assess students’ skill or understanding, either by observing the students’ activity or directly administering a test.

Despite this common paradigm, education and medicine differ greatly in how they treat research in their practice. Every good-quality medical school has a teaching hospital, at which researchers and practitioners jointly work to improve research and practice. In contrast, high-quality education schools do not have Research Schools that bring together research and practice to advance teaching and learning.

Educators need Research Schools – an institution comparable to the teaching hospital with the express goal of connecting the work of researchers and practitioners in order to craft research methods and questions that address important issues in
education. We propose that universities and schools join together to create Research Schools – real-life schools (public and private) affiliated with universities where educators and researchers work together to create research that relates to educational practice and policy and to train future practitioners and researchers (Hinton and Fischer, 2008).

Over a century ago in 1896 John Dewey proposed what came to be called “laboratory schools,” which he proposed would serve this function. He began the Laboratory School at the University of Chicago to test practices in vivo based on hypotheses from psychology and cognitive science. Unfortunately, today almost all so-called laboratory schools have no involvement in research, but instead function as elite schools to provide excellent education for children of faculty and students at universities. Despite the name, they do not serve the function that Dewey proposed. Educational neuroscience faces the problem that Dewey described – little or no connection between educational practice and research on learning and teaching. The establishment of Research Schools can help to solve this problem by creating institutions whose purpose is to produce a strong research foundation for educational practice and policy.

A central challenge to educational neuroscience is how to bring educational insights into brain development and brain mechanisms into classrooms. The ultimate agent of change in the educational system is the teacher, and so the development of infrastructures that bring teachers and researchers together is an important goal. One possibility is that NSF could form partnerships with the Department of Education to foster Research Schools and school-researcher partnerships. One role of NSF would be to provide templates or “model protocols” of how to study questions in brain-based learning. Schools could then work with local universities to apply the protocols to questions of interest to them, such as: Will a specific curriculum work in my school setting? The role of the templates would be to model study design (for example, the importance of including appropriate control groups, the benefits of randomised-controlled-trial designs, etc.). These supports would help individual teacher-researchers do effective research and not have to “reinvent the wheel” each time.

Another (complementary) role would be for NSF to directly foster the creation of Research Schools by supporting collaborations between scientists and teachers and the formation of a network of Research Schools that can support each others’ efforts. The International Mind, Brain, and Education Society (IMBES) is working to create such a network of Research Schools in the U.S. and around the world. The Research Schools could help promote changes in school culture, establishing the expectation, for example, that empirical research on education principles and products are an intrinsic part of their mission. When schools get involved in research, we expect it to have a transformative impact on their delivery of education and on the research questions addressed in universities. There are already a few model schools of this kind in the U.S. and elsewhere, which could provide the relevant expertise and experience for creating paradigms for Research Schools.

A related point of leverage in the system is initial teacher training and continuing professional development. Schools of Education need to teach the application of evidence-based standards, starting with research design and statistics. An important
example for educational neuroscience is that teachers need to know that neural data are not privileged, but are subject to the same biases and difficulties of interpretation as data yielded by any experimental method. Supporting teachers in understanding how to evaluate the claims made by the “brain-based learning” industry is crucial given the privileged role of the teacher as an agent of educational change.

Creating a New Generation of Interdisciplinary Researchers

Educational neuroscience requires innovation in research training regarding methods, assessments of teaching and learning, analysis of courses, curriculum, and informal learning environments, and continuing professional development. Bringing together the disciplines required (education, psychology, neuroscience, genetics, development, and others) means dealing with different philosophies underpinning research (such as the quantitative methods of the natural sciences versus the philosophical inquiry of the humanities) and providing rigorous training in research methods. The different research methods of the natural sciences and humanities are complementary rather than mutually exclusive, yet they are often put in juxtaposition within education faculties. What is needed is to build a new community of researchers who are expert in the multiple contributing disciplines and who investigate learning and teaching systematically in education settings, perhaps called a neuroeducator (Gardner, 2008). A genuinely inter-disciplinary training environment is required. This need presents a substantial challenge for research methods as they are traditionally taught within Education. Such inter-disciplinary training would begin with bringing together different research communities, ideally led by faculties of Education.

Creating Educational Engineers

Another infrastructure change that will promote educational neuroscience is to produce a new category of educators – educational engineers – who specialize in making useful connections between practice and research. They will have expertise at translating or applying findings from cognitive science and neuroscience to learning in classrooms and other educational settings, including curricula, educational software, children’s television, and design of playgrounds and sports products and fields. In older sciences, such as physics, chemistry, and biology, the role of engineer or translator has been established and respected for a long time. The models and knowledge from these sciences do not automatically translate to practical questions, such as building a bridge, creating a new kind of skin cream, or preventing invasive species from destroying native species in inland lakes. Businesses and governments depend on engineers in physics and similar specialists in other fields to connect scientific knowledge with such issues of practice.

Education needs this kind of specialist, perhaps called an education engineer or a second kind of neuroeducator (Gardner, 2008). An obvious place to train this new kind of specialist would be Research Schools. Fortunately institutions already exist where some professionals work to build connections between research and practice in education. Sesame Street Workshop is renowned for its use of formative evaluation and practical assessment to shape its many educational programs on television and in other media (Lesser, 1974). Some education companies and nonprofits also train educators
with these kinds of practical skill. For example, the Center for Applied Special Technology (www.cast.org) creates educational software to facilitate and support learning and teaching, focusing especially on supports for diverse learning pathways (Rose & Meyer, 2002).

**Improving Data Bases on Learning and Development**

A fundamental infrastructure to provide a strong scientific groundwork for learning and teaching is the creation of large data bases about learning and development, including brain and genetic data. Such data bases have great potential usefulness for both research and practice. For example, the U.S. database for traffic safety, the Fatality Analysis Reporting System, shows how useful a comprehensive data base can be (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, etc. The effects of this data base on traffic safety have been far-reaching and deep, contributing substantially to an enormous reduction in traffic fatalities and injuries over the last 40 years. Data bases for educational neuroscience, including evidence about how educational practices function in real-life settings, can have similar far-reaching influence.

Fortunately a few data bases already exist that are relevant for educational neuroscience, including the National Assessment of Educational Progress, the Child Language Data Exchange System (which assesses language development), the NICHD Early Child Care Research Network, the NIH MRI Study of Normal Brain Development, and the state data bases that have resulted from No Child Left Behind. As useful as these data bases are, however, they have major gaps, which can be readily remedied. They mostly include either behavioral or biological assessments, not both. In general, they omit data on learning and teaching in classrooms, with computers, or in other education settings.

Data bases are needed that combine biological markers relevant to learning with evidence of learning and teaching in real-life settings, not just performances on standardized tests in environments that are not dedicated to learning. Of course, neuroimaging and genetic information are not better under all circumstances, but educational population studies (making use of, for example, a brain imaging machine in the school basement to measure students’ electroencephalograms) are likely to produce evidence about relations between learning pathways and neural development, as well as evidence relevant to formal and incidental learning. Research Schools are a natural setting for collecting these kinds of data, and combined with traditional standardized assessments such data bases can move the field beyond ideology and opinion to evidence-based practice and policy.

An important direction for data collection is to test the assumptions made by the current educational system regarding how development occurs and what should be taught, with the goal of creating models of common learning pathways and variations. For example, in the area of numeracy, work on the basic “number sense” in the parietal lobe shared by humans and animals and used for estimating approximate number at a glance has raised questions about assumptions concerning the optimal number
curriculum. Neuroscientists showed the existence of specialised cells in the brain that respond to specific numbers (e.g. neurons that are most responsive to “3”) and demonstrated that even infants have a degree of numerical competence for small specific numbers and for general judgments of quantity (Dehaene, 1997). These findings indicate that small numbers and relative size can be perceived directly at an early age.

Do these findings indicate that educators can build directly on the rudimentary brain-based ability to perceive numbers, moving quickly to teach the cultural tools of number words and Arabic digits? Further research on early development of numbers indicates that starting with these elementary perceptual capacities, children build the digits (1, 2, 3, 4) into a representation (mental model) of the number line, gradually constructing it one number at a time during the preschool years (Carey, 2009; Le Corre et al., 2006). Their construction of the mental model of the elementary number line sets the stage for using the number line more broadly and deeply when they begin to learn arithmetic (Griffin & Case, 1997). Research on learning pathways and the roles of mental models in education will provide useful knowledge about learning patterns and differences.

To improve data bases and make it possible to address essential research questions in educational neuroscience, three issues require attention:
1. encouraging multi-site studies,
2. asking grant holders to use common measures across domains, and
3. using genetically and neurologically informed designs.

Encouraging Multi-Site Studies
Multi-site studies are important because (1) studies need to sample diverse learners to represent the full range of learning pathways and (2) longitudinal studies of typically developing populations require large numbers, probably beyond the capacity of any single research center. Carrying out multi-site studies requires using shared protocols and measures. These studies should also track environmental inputs in standard ways, including measures of developing behavior, SES (not just income, but correlated factors such as nutrition, breast feeding experience, etc.), emotional development, and availability of educational resources. Interpretation of results will be greatly facilitated if measures are agreed in advance for multiple sites.

Asking Grant Holders to Use Shared Measures in their Studies
Besides using common measures in multi-site studies, another way to improve the quality of databases is to ask researchers receiving grants to include a few core neural and behavioral measures in their investigations, even if the measures do not form part of the dominant hypotheses in their particular area of inquiry. Choosing such measures will require recommendations from a panel of researchers and educators representing a wide range of areas of expertise. This strategy will help in gathering information about developmental pathways and likely causal patterns.

Large databases concerning developmental pathways are needed to tackle research questions concerning how core skills and structures develop similarly and differently across a range of real-life conditions. These large databases will also enable
a deeper understanding of co-morbidity – why certain learning strengths or difficulties co-occur systematically, such as the co-morbidity between attention deficit hyperactivity disorder, dyslexia, and other learning disorders. The use of shared measures across domains of learning and disorder will provide a much broader foundation for tackling questions of co-morbidity, difference, and complexity.

**Encouraging Designs Informed by Neuroscience and Genetics**

One of the common neuromyths is that specific functions such as language and mathematics are located in one spot in the brain, when in fact they involve orchestration of activity across many regions. Indeed one of the best candidates for neural foundations of cognitive development is the coordination of brain activity as measured by coherence across brain regions. For example, infants who are learning to crawl show a surge in coherence between prefrontal and occipital/parietal sites within each hemisphere (Bell & Fox, 1996). Research in educational neuroscience can usefully examine activity across the whole brain, as well as in targeted “regions of interest” (such as the parietal lobes for studies involving numbers or the motor cortex for crawling). Illuminating development and diversity of learning requires information about how critical neural areas develop links to other areas. Studies of connectivity are likely to have special relevance to educational questions (Hanlon et al., 1999).

Similarly, genetic markers provide powerful opportunities for uncovering biological roots of development and learning. For example, data from epigenetics (the impact of environments on gene expression and gene interactions) indicate that genetically informed designs can improve understanding of environmental effects on learning, such as showing that genetic effects occur under some environmental conditions but not others. The field of genetics has gone beyond simple genetic determinism, which should be reflected in educational research designs.

These several recommendations for strengthening the infrastructure for educational neuroscience will not only improve the research foundations of this emerging field, but also provide a sound basis for connecting research to practice and policy. 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 in educational neuroscience, 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 with Educational Neuroscience**

The Mind, Brain, and Education 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 four new forms of infrastructure: (1) Research Schools in which researchers and practitioners work together to craft research questions and methods to shape practice and policy, (2) a new kind of researcher who has the interdisciplinary skills required to grow the new field of educational neuroscience, (3) a new kind of professional who specializes in connecting practical questions with research findings and concepts, an educational engineer, and (4) large shared data bases on learning and development. In addition, an informed debate on neuroethics with respect to mind, brain and education is essential.

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. Educational neuroscience and more broadly mind, brain, and education have an important role to play in improving education in the 21st century.

References


