



Scientific and Pragmatic Challenges for Bridging Education and Neuroscience

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Educational neuroscience is an emerging effort to integrate neuroscience methods, particularly functional neuroimaging, with behavioral methods to address issues of learning and instruction. This article consolidates common concerns about connecting education and neuroscience. One set of concerns is *scientific*: in-principle differences in methods, data, theory, and philosophy. The other set of concerns is *pragmatic*: considerations of costs, timing, locus of control, and likely payoffs. The authors first articulate the concerns and then revisit them, reinterpreting them as potential opportunities. They also provide instances of neuroscience findings and methods that are relevant to education. The goal is to offer education researchers a window into contemporary neuroscience to prepare them to think more specifically about the prospects of educational neuroscience.

Keywords: brain; development; dyscalculia; dyslexia; education; math; mathematics; neuroscience; reading

Neuroscience has experienced rapid growth in recent years, spurred in part by the U.S. government's designation of the 1990s as "The Decade of the Brain" (Jones & Mendell, 1999). The rapid development of functional neuroimaging techniques has given researchers unprecedented access to the behaving brains of healthy children and adults. The result has been a wave of new insights into thinking, emotion, motivation, learning, and development. As these insights suffuse the social sciences, they sometimes inspire reconsideration of existing explanations. This is most true in psychology, as marked by the births of cognitive neuroscience (Gazzaniga, Ivry, & Mangun, 2002), developmental neuroscience (Johnson, Munakata, & Gilmore, 2001), and social neuroscience (Cacioppo, Visser, & Pickett, 2005). It is increasingly true in economics, where the rapid rise of neuroeconomics (Camerer, Loewenstein, & Prelec, 2005) has caught the attention of the popular press (Cassidy, 2006). Other social sciences, including communication (Anderson et al., 2006), political science (McDermott, 2004), and sociology (Wexler, 2006), are just beginning to confront the question of whether their research can be informed by neuroscience.

Education is somewhere between the two poles of early adopters and tentative newcomers. A decade ago, in this journal, Bruer (1997) forcefully considered the relevance of neuroscience to education. His conclusion—that neuroscience is "a bridge too far"—was noteworthy because Bruer was then director of the McDonnell Foundation, which was actively funding research in both disciplines. Although it was in his best interests to find connections between the disciplines, he found instead poorly drawn extrapolations that inflated neuroscience findings into educational neuromyths. Since Bruer's cautionary evaluation, a number of commentators have considered the prospects for educational neuroscience. Many sound a more optimistic note (Ansari & Coch, 2006; Byrnes & Fox, 1998; Geake & Cooper, 2003; Goswami, 2006; Petitto & Dunbar, in press), and a textbook has even appeared (Blakemore & Frith, 2005).

In this article, we negotiate the middle ground between the pessimism of Bruer and the optimism of those who followed. Table 1 summarizes eight concerns about connecting education and neuroscience. Some are drawn from Bruer (1997) and the ensuing commentaries. Others come from conversations with colleagues in both disciplines, and still others from our own experiences. These concerns do not seem to represent a blanket dismissal but rather a genuine curiosity (tempered by a healthy skepticism) about the implications of neuroscience for education. We begin by articulating the concerns along with some facts about neuroscience that make the concerns more concrete. We voice them in the strong tone in which we have heard them espoused. We then revisit the concerns, reinterpreting them as potential opportunities (also in Table 1). This approach permits us to review a selection of neuroscience studies relevant to content learning. We focus on recent functional magnetic resonance imaging (fMRI), or neuroimaging, studies for reasons of space and because these are the findings that have captured the most attention, both in the academy and in the popular press. Ideally, our review illustrates some elements of neuroscience so that education researchers can think more specifically about the prospects of educational neuroscience.

We conclude with two reflections on moving from armchair arguments of a philosophical nature to scientific action on the ground. First, we argue that education and neuroscience can be bridged if (and only if) researchers collaborate across disciplinary lines on tractable problems of common interest. It is the success

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Table 1
Summary of Concerns and Opportunities

Aspect	Concern	Opportunity
Scientific		
1. Methods	Neuroscience methods do not provide access to important educational considerations such as context.	Innovative designs can allow neuroscience to study the effects of variables of interest to education, such as context.
2. Data	Localizing different aspects of cognition to different brain networks does not inform educational practice.	Neuroscience data suggest different analyses of cognition and may therefore imply new kinds of instructional theories.
3. Theories	Reductionism is inappropriate.	Reductionism is appropriate if it is not eliminative.
4. Philosophy	Education and neuroscience are incommensurable.	Neuroscience may help to resolve some of the incommensurables within education.
Pragmatic		
5. Costs	Neuroscience methods are too expensive to apply to education research questions.	Educationally relevant neuroscience might attract additional research funding to education.
6. Timing	We do not currently know enough about the brain for neuroscience to inform education.	There are already signs of success.
7. Control	If education cedes control to neuroscience, it will never regain its independence.	Ask not what neuroscience can do for education, but what education can do for neuroscience.
8. Payoffs	Too often in the past, neuroscience findings have turned into neuromyths.	People like to think in terms of brains, and responsible reporting of cumulative results can help them.

or failure of these collaborations, and not logical arguments for or against connecting the two disciplines, that ultimately will determine the fate of educational neuroscience. Second, we argue for a cautious optimism. Neuroscience cannot replace education, nor is that the goal of educational neuroscience. There are limitations on what neuroscience can tell us about the social and contextual matrix that is so powerful for learning. If education researchers are not mindful of these limitations—if they buy into the hard sell—they will find themselves disappointed by the scope and pace of progress. If, on the other hand, they understand the limitations of neuroscience methods and employ them in a complementary manner, then there is reason to be optimistic about the future prospects of educational neuroscience.

Concerns About Connecting Education and Neuroscience

We are not the first to notice that education and neuroscience are quite different disciplines, and it is unclear whether they can inform each other. In this section, we distill the primary differences into eight commonly expressed concerns about connecting education and neuroscience. These concerns come in two clusters—scientific and pragmatic.

Scientific Concerns

The first cluster addresses the scientific distance between education and neuroscience. Do their different methods, different data, and different theories constitute a fundamentally unbridgeable divide?

Concern 1. Methods: Neuroscience methods do not provide access to important educational considerations such as context. The methods of a science constrain and circumscribe its data and theories. Neuroscience methods demand highly artificial contexts and thus cannot provide useful data or theories about classroom contexts.

The application of neuroscience methods to social science research questions has increased dramatically with the development of new technologies for noninvasively measuring brain activity in behaving humans. One branch of neuroscience—neuropsychology—historically has had an important connection with education, particularly with respect to behavioral assessments of potential neurological problems, including attention deficit hyperactivity disorder, fetal alcohol syndrome, and early exposure to neurotoxins (see D’Amato, Fletcher-Janzen, & Reynolds, 2005). The new instruments of neuroscience allow researchers to examine brain function directly rather than inferring it from behavioral assessments. These tools enable a better understanding of typically and atypically functioning brains. However, the new methods have limitations in comparison with neuropsychology. Most notably, they do not permit assessment in the field, for example, by a school psychologist.

Different functional neuroimaging methods have different strengths and weaknesses. The *temporal resolution* of a method is how well it can measure rapid changes in brain activity. The *spatial resolution* is how precisely it can localize the source of the activity. Event-related potentials (ERPs) and fMRI provide a good example of how temporal and spatial resolutions trade off in current methods. Electrodes touching the scalp can measure ERPs—changes in the brain’s electrical activity time-locked to external events such as stimulus presentation. ERPs give precise temporal resolution, on the order of milliseconds. However, ERPs have poor spatial resolution, licensing only coarse inferences about the localization of activity. By contrast, fMRI provides good spatial resolution, on the order of millimeters. However, its temporal resolution is poor: The measurement of brain activity is limited by blood flow changes that take several seconds to occur.

Although we will draw our examples primarily from fMRI studies, it is important to remember that this method, like all

neuroscience methods, has limitations and that its limitations constrain the kinds of research questions that it can answer. (See Gazzaniga et al., 2002, for a discussion of the trade-offs among neuroscience methods.) For this reason, most research questions in neuroscience are addressed by multiple methods, sometimes in the same study.

A shared limitation of most brain-recording methods is their obtrusiveness and dependence on highly controlled environments. In fMRI experiments, participants must lie perfectly still inside cramped cylindrical magnets. The scanner is extremely noisy. These constraints make it challenging to run studies with young children.¹ In most fMRI paradigms, participants view stimuli projected on a small hanging mirror because metal objects cannot be introduced into the powerful magnetic field. The magnetic fields do not directly measure neural activity; instead, they enable detection of changes in blood flow as the vascular system replenishes nerve cells *a few seconds after* increased neural activity (i.e., the hemodynamic response). People's responses typically are limited to pressing buttons. Verbal responses are often avoided because they are difficult to record in the noisy environment and because jaw movement can cause artifacts (i.e., distortions that render images uninterpretable).

The brain is a busy place, with all regions requiring blood at all times. To obtain a task-relevant signal that rises statistically above the background noise, participants must perform a task for many trials. Participants also need to perform a control task many times. The brain location of task-relevant activation typically is identified by subtracting task-irrelevant activation as measured by the control task. For example, researchers interested in the neural correlates of magnitude comparison might employ the following experimental and control tasks: In the experimental task, participants might repeatedly judge whether digits shown one at a time are greater or smaller than the digit 5; in the control task, they might passively view digits shown one at a time but without making a comparison with 5. By subtracting the activation for passive viewing from the activation for active comparison, the common activation due to processing the symbolic forms of digits can be removed, leaving only the activation unique to magnitude comparison.

The context of interest for neuroscientists is the brain, and the limited environment of the scanner usually is sufficient for triggering measurable changes in brain context. By contrast, for the educator the relevant context is the mind and its environment. Thought and learning are profoundly determined by the broader context, and this is important because educators can orchestrate contexts to enhance learning. Unfortunately, interesting educational contexts seem beyond the reach of current neuroscience methods. Good teaching, for example, involves affecting highly variable contexts rather than presenting a simplified stimulus set. The norms that regulate classroom interaction do not seem describable as patterns of activation. To take one example, many mathematics educators believe that children should apprentice in mathematical cultures to master their symbol systems and modes of thinking (Cobb & Yackel, 1996). Contrast this with the methods of neuroscience, which involve hundreds of trials processing nearly identical stimuli. If neuroscience insinuates itself into education, we may be restricted to views of instructional activities that conform to the limitations of neuroscience methods. We

may lose access to the contextual variables and interactions that most affect educational practice.

De-emphasis of contextual variables would not be a surprising outcome of an educational neuroscience. The strengths and weaknesses of fMRI match the goals of neuroscience, which include investigating neural mechanisms but not the effects of context on learning or assessment. On questions of context, neuroscience might simply be silent. Moreover, neuroscience is a biological science, and it will naturally gravitate toward biological solutions to learning problems rather than instructional ones.

Concern 2. Data: Localizing different aspects of cognition to different brain networks does not inform educational practice. An important goal of neuroscience is to analyze cognition into elementary functions and to identify neural correlates of those functions. Neuroscientists collect data on the brain areas that are selectively activated during language comprehension, mathematical reasoning, and other cognitive activities. However, knowing the location of an elementary cognitive function tells us nothing about how to design instruction for teaching that function, just as knowing where the alternator resides in an engine tells us nothing about how to teach driving. Does it really matter for reading education whether phonology is processed by Broca's area, Wernicke's area, the angular gyrus, or the fusiform gyrus?

One might argue that mapping the brain will eventually support useful theories of complex cognition and instruction. Yet the history of behaviorism provides a cautionary parallel. Although behaviorism is not about localization, it similarly espouses a commitment to a specific class of data. Early behaviorism was about discovering how reinforcement affects behavior, often using animals as subjects. It was argued that once these empirical relations were sufficiently understood, it would be possible to scale up behaviorist theories to explain more complex forms of learning such as language acquisition (Skinner, 1957). However, it has proved quite difficult to build from data about reinforcement learning, for example, to a satisfactory theory of language acquisition (Chomsky, 1959). So, too, it will be difficult to scale up from data about brain location to explain levels of cognition that educators care about.

Concern 3. Theories: Reductionism is inappropriate. Every science evolves an appropriate vocabulary that supports meaningful generalizations within the domain of study while avoiding irrelevant distinctions. The vocabulary of education supports the description of learning as it occurs inside and outside classrooms. Neuroscience is a lower level science than education, and its vocabulary is therefore too microscopic to support useful generalizations for education. If educational terms of proven value at the level of behavior and practice were replaced by clusters of neuroscience terms specifying neurotransmitters, cell types, brain areas, genetics, and so forth, the result would be too cumbersome to be a useful description of classroom learning.

An instructive analogy is the reduction of mathematics to logic, which Whitehead and Russell (1910–1913) attempted in their three-volume *Principia Mathematica*. The proof of $1 + 1 = 2$, a statement understood by young children, does not occur until p. 379 of the second volume, where it requires half a page of

logical symbols. Mathematicians would have inherited an accounting nightmare if they had switched to the fine-grained vocabulary of logic, and so they did not. Analogously, education researchers would gain nothing from translating their theories into the terminology of neuroscience.

Even if the vocabulary of education could be comfortably reduced to that of neuroscience, the result would be of no practical significance. What is the value of substituting a neuroscience description of a phenomenon for its educational equivalent (Byrnes & Fox, 1998)? For example, consider a child who has difficulty in determining the larger of two numbers. An education researcher might describe this as a difficulty in comparing the cardinal values of number symbols. Nothing is gained by redescribing it as a dysfunction of the intraparietal sulcus.

Concern 4. Philosophy: Education and neuroscience are incommensurable. The differences in the vocabularies of education and neuroscience might ultimately be too great to allow multidisciplinary theorizing. The vocabulary of education belongs to the social sciences and includes *mental* terms such as *understanding* and *identity*. It is tailored for the description of *behavioral* phenomena—both psychological and social. By contrast, the vocabulary of neuroscience belongs to the biological sciences. It includes *material* terms such as *hemodynamic response* and *white matter tract*. It is tailored for the description of *physical* phenomena. These differences are problematic. Cartesian dualism might preclude any reconciliation between the mental terms of education and the material terms of neuroscience (Byrnes & Fox, 1998). But even if reconciliation is possible, for example, through some sort of correlation between mental and material terms, problems remain. Durkheim (1950) claimed that “the determining cause of a social fact should be sought among the social facts preceding it and not among the states of individual consciousness” (p. 110). If he is right, then explaining classroom causality by referring to physical mechanisms is simply an error.

Pragmatic Concerns

Even if the scientific gulf between education and neuroscience can be bridged in principle, doing so may be too difficult in practice. The pragmatic difficulties that face educational neuroscience can be distilled into four concerns.

Concern 5. Costs: Neuroscience methods are too expensive to apply to education research questions. We cannot simply ask about the expected benefits of educationally relevant neuroscience studies; we must also ask about the associated costs. It costs roughly \$600 per participant hour to conduct an fMRI experiment. Most fMRI studies use an affiliated hospital’s scanner and its mandatory support staff, and many participants are scanned late at night when the scanner is not being used for clinical purposes. Compare this infrastructure cost with the \$10 paid to a participant for an hour in a conventional laboratory experiment, or the \$0 paid to students in a classroom experiment. A cost-benefit analysis does not support the much higher spending required for each neuroscience data point, given the expected scientific benefit.

Even if the money were spent and the resulting neuroimaging studies yielded educationally relevant insights, the cost of widespread deployment would loom over the project. It is fiscally

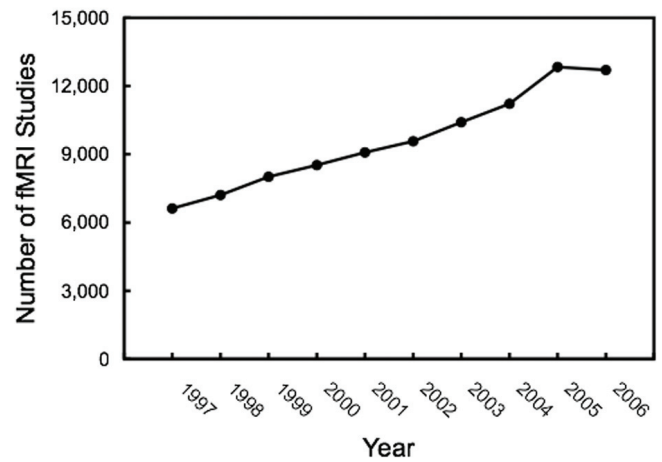


FIGURE 1. Growth of the fMRI literature over the past decade, by number of studies published per year. The results were obtained from the National Institutes of Health’s PubMed database (<http://www.ncbi.nlm.nih.gov/entrez/>) on May 9, 2007, using the following query: “fMRI” OR “functional MR” OR “functional MRI” OR “functional magnetic resonance imaging.” Only empirical studies of human participants were counted.

unimaginable to scale up neuroscience methods to test, sort, and track large populations of students.

Concern 6. Timing: We do not currently know enough about the brain for neuroscience to inform education. Although neuroscience is a discipline with a long history, only recent and ongoing technical developments have enabled the noninvasive study of typical brains engaged in complex cognition. The fruits of these technical developments have been nothing short of astounding. Figure 1 indicates the linear increase in new fMRI studies published each year since Bruer’s 1997 article. The cumulative number of fMRI studies is increasing quadratically, and this excludes other techniques such as ERPs, magnetoencephalography, and positron emission tomography. It remains for neuroscientists to digest this mass of data and deliver theories of brain function at an appropriate level for application to education.

Thus far, the bulk of fMRI studies have not been especially informative for education. Although elegant, they use relatively simple tasks from a behavioral perspective. But as the methods have matured, neuroscientists have begun to study more complex forms of cognition such as discourse comprehension (Mason & Just, 2006). Education researchers should wait for these more relevant data to be collected and distilled into succinct theories.

Concern 7. Control: If education cedes control to neuroscience, it will never regain its independence. This is perhaps the most insidious concern. Many education researchers with whom we have spoken view neuroscience as a threat to their discipline. Neuroscience has ascended, both in the popular imagination and in the academy. Images of the brain coupled with material explanations appear to command more authority than the functional explanations of social science. Within the academy, new neuroscience programs

have cannibalized resources from other disciplines. Education researchers see what is happening in psychology, where theories are increasingly cast in terms of neural mechanisms and debates increasingly turn on imaging data. Some education researchers may anticipate a similar fate if they allow neuroscience in the door.

Concern 8. Payoffs: Too often in the past, neuroscience findings have turned into neuromyths. Whatever we might hope for a future educational neuroscience, most seeming payoffs thus far have been neuromyths. Bruer's (1997) article pointed to irresponsible extrapolations of basic neuroscience research on critical periods, environmental enrichment, and synaptogenesis. Much of this research had been conducted on animals by means of sensory and motor tasks. Bruer pointed out that there is simply too much distance between this research and the questions of education to draw meaningful and defensible implications. He was particularly worried that an undue focus on the learning of preschool children would draw attention away from the remarkable range of knowledge and skills that people acquire throughout their lifetimes. Many other neuromyths exist in education (Goswami, 2006). What is common to all is the inflation of basic neuroscience findings of limited scope into educational advice of dubious value.

More alarmingly, neuromyths have escaped beyond academia and are being marketed directly to school administrators and teachers. Commercial programs describe simple physical exercises for "switching on the brain before a lesson," "increasing information flow between the left and right hemispheres," and so on. Regardless of the efficacy of these programs, their claims are not founded on what is actually known about brain function. What started as neuromyths have degenerated further into neuromarketing.

Concerns as Opportunities

The eight concerns represent significant challenges to educational neuroscience. In this section, we cycle through them a second time with the perspective that each also represents an opportunity for new and innovative research.

Revisiting the Scientific Concerns

The four scientific concerns reflect in-principle problems with connecting education and neuroscience. If the divide between the disciplines is fundamentally unbridgeable, then collaborations between education researchers and neuroscientists ultimately will fail. An alternative view is that the disciplines are complementary, with many potential synergies.

Opportunity 1. Methods: Innovative designs can allow neuroscience to study the effects of variables of interest to education, such as context. A powerful way to improve education is to design and implement new learning contexts and interactions. Even though the context of a scanner is necessarily spare, fMRI experiments can be used to measure differences in brain activity after students have experienced different contexts. For example, Delazer et al. (2005) compared two ways of learning novel arithmetic operations. In the memorization condition, participants simply associated operands with results. In the strategic condition, they learned an algorithm for transforming operands into results. The instructional parallel would be

memorizing math facts as compared with learning to compute them (Baroody, 1985). A subsequent fMRI scan revealed that participants in the memorization condition showed greater activation in a network of brain areas specialized for the retrieval of verbally coded information (including the angular gyrus). Conversely, participants in the strategic condition showed greater activation in a network of brain areas involved in controlled visuospatial processing (including the inferior precuneus and the anterior cingulate cortex). This result suggests the use of spatial working memory to store intermediate results during execution of the algorithm. Thus the study makes the point, obvious to education researchers, that different learning contexts can lead people to adopt different strategies to solve the same problems. More important, it illustrates how neuroscience methods can be used to detect and understand such differences.

Neuroscience also brings new perspectives to the study of development that may be useful to education research. Rivera, Reiss, Eckert, and Menon (2005) imaged children between the ages of 8 and 19 as they solved simple arithmetic problems. Behaviorally, the researchers found that speed increased with age (although accuracy did not—all children could solve all problems equally well). The neuroimaging data "opened the hood" to reveal that the continuous improvement in speed was *not* the result of a continuous change in the efficiency with which a particular brain area performed a particular process. Rather, it was the result of a transition from domain-general processing to domain-specific processing. Younger children recruited general memory and reasoning areas (including the medial temporal lobe, the basal ganglia, the middle frontal gyrus, and the anterior cingulate cortex). By contrast, older children used visual and verbal areas (including the fusiform gyrus and the supramarginal gyrus). A continuous change in behavior belied an important cognitive shift, one that neuroscience methods could detect. This study raises the possibility of designing activities that help children to shift from domain-general to domain-specific modes of thought.

Neuroscience methods can also be used to study the effects of cultural variables. For example, Tang et al. (2006) imaged native English- and Chinese-speaking participants as they added and compared Arabic numbers. English participants showed greater activation in language areas (including Broca's and Wernicke's areas), whereas Chinese participants showed greater activation in motor areas (including the premotor area and the supplementary motor area). The researchers speculated that this was a consequence of the fact that Chinese children are taught arithmetic using the abacus and appear to retain a visuomotor understanding of numbers even as adults. This study raises a number of interesting educational questions. For example, children are often introduced to place-value through manipulation of base-10 blocks. When they later reason without manipulatives, do they show residual activation in motor areas? If so, does this have implications for the sequencing of hands-on and paper-and-pencil lessons?

Opportunity 2. Data: Neuroscience data suggest different analyses of cognition and may therefore imply new kinds of instructional theories. An important goal of cognitive neuroscience is to understand the neural bases of cognition. In the past, this involved starting with psychological constructs, such as working memory, and identifying their neural correlates. Increasingly, however, neuroscience

studies reveal novel analyses of cognition into elementary functions that are invisible at the behavioral level (Byrnes & Fox, 1998).

For example, adults solve single-digit multiplication problems faster than single-digit subtraction problems (Campbell & Xue, 2001). One explanation of this difference is that both tasks are performed by retrieving facts from a mental “lookup table.” People may have more experience with multiplication than with subtraction, so they are faster at looking up answers. A different explanation, emanating from the neuroscience literature, is that multiplication and subtraction use different strategies implemented by different brain networks (Dehaene, Piazza, Pinel, & Cohen, 2003). In particular, multiplication recruits a network of brain areas known to be involved in verbal processing (including the angular gyrus). This is consistent with retrieval of verbally coded multiplication facts—a fast strategy. By contrast, subtraction recruits a network of brain areas implicated in visuospatial processing (including the intraparietal sulcus). This suggests that subtraction requires reasoning about the magnitudes of numbers, a comparatively slower process. The neuroscience explanation of the behavioral difference between multiplication and subtraction—that they are performed using different brain networks that implement different strategies—raises a number of interesting questions. For example, collaborative research between mathematics education and neuroscience could investigate whether this strategic difference is a consequence of the different ways that the operations are taught and practiced.

Opportunity 3. Theories: Reductionism is appropriate if it is not eliminative. Reduction is a unifying principle of science: The macroscopic terms of coarse-grain sciences are coordinated with the microscopic terms of fine-grain sciences. This is the time-honored process by which the sciences are stitched together. Partial unification of education and neuroscience, if it comes, should be welcomed. What is problematic is *eliminative reductionism* (Churchland, 1989). This is the doctrine that neuroscience explanations should replace—not just anchor or enrich—behavioral explanations (Byrnes & Fox, 1998).

A classic example of reduction is statistical mechanics. Newton formulated classical mechanics in the 17th century; Carnot proposed thermodynamics in 1824. Initially, these were considered incommensurable theories belonging to different disciplines. It was not until the late 1800s that Boltzmann, Gibbs, and others formulated statistical mechanics, which reduces thermodynamics to classical mechanics. For example, the thermodynamic notion of temperature reduces to the mechanical notion of mean kinetic energy. However, thermodynamics was not reduced away—chemists, chemical engineers, and others continue to use its more macroscopic terms *when appropriate*. Similarly, reducing select educational terms to neuroscience terms will not eliminate them. Rather, it will make it possible for education to recruit the microdescription of neuroscience when necessary and for neuroscience to recruit the macrodescription of education when necessary.

Biology provides a good example of how to maintain levels of analysis within a reductionist paradigm. It makes a corridor of explanations from molecular biology all the way up to ecology and zoology. Explanations at lower levels are consistent with those at higher levels but do not replace them. Rather, their relationships are

complementary and supplementary—witness the existence of the journals *Molecular Ecology* and *Journal of Experimental Zoology Part B: Molecular and Developmental Evolution*. One can imagine an analogous corridor of explanation from neuroscience to education. This proposal is not new. It originates with Bruer (1997), who observed that even if bridging from education to neuroscience in a single span proves impossible, a system of smaller bridges might be possible: for example, from instruction to cognitive psychology and from cognitive psychology to cognitive neuroscience.

Opportunity 4. Philosophy: Neuroscience may help to resolve some of the incommensurables within education. Pointing to the incommensurables between education and neuroscience ignores the incommensurables within education itself. In education, different theoretical constructs are used to study different dimensions of task performance—cognitive, motivational, emotional, social, cultural—and the results are published in different journals. Cognition, for example, is often treated as “what gets a task done,” whereas motivation is treated as “what gets people to try a task.” There is little vocabulary for connecting these two aspects of learning. Neuroscience might help to resolve some of the balkanization within education because it provides a common biological vocabulary for describing phenomena and a common reporting scheme for describing the results of neuroimaging experiments.

One example of how neuroscience can accommodate multiple dimensions of learning is research on the brain’s “reward system” (Montague, King-Casas, & Cohen, 2006). The internal reward system not only is responsible for motivating behavior but also modulates learning. A key to the internal reward system is the neurotransmitter dopamine. Dopamine increases when there is a discrepancy between an expected and a realized external reinforcement (e.g., food, money). For example, if people expect a low payoff and receive a high one (or vice versa), dopamine increases. However, if people expect a high payoff and receive a high payoff, dopamine does not increase. The dopamine system helps to adjust people’s expectations, which is a form of learning. The initial research on dopamine used animals, single-cell recordings, and reinforcements such as fruit juice. More recent research on the internal reward system has been extended to include social dimensions of human performance. For example, Rilling, Sanfey, Aronson, Nystrom, and Cohen (2004) used fMRI to study dyads as they played a game that allows for both cooperation and competition. The reinforcement in this case was money. The researchers found that the brain incentivizes cooperation: Greater cooperation was associated with greater activation in the reward system (including the striatum and the ventromedial prefrontal cortex).

The reward system is also sensitive to emotional dimensions of performance. For example, Sanfey, Rilling, Aronson, Nystrom, and Cohen (2003) found that the more unfair (i.e., emotionally negative) an interaction, the greater the activity of the reward system (specifically the insula). The neuroscience notion of an internal reward system naturally unifies what typically are treated as disparate dimensions within education: motivation, emotion, social factors, and learning. It is an interesting question whether this research can also inform our understanding of how the reward structure of the

classroom affects learning. For example, recently the dopamine system has been shown to be recruited by purely cognitive feedback (e.g., by awareness of having given correct or incorrect answers) that does not involve any overt external benefit (e.g., Tricomi, Delgado, McCandliss, McClelland, & Fiez, 2006).

The place-based reporting scheme of neuroimaging also helps to unify the results of different studies even when they address different phenomena. Neuroimaging papers describe the activation peaks from each experiment using standardized brain coordinates. This place-based organization makes it possible to identify the networks of brain areas that consistently coactivate across populations and tasks.² For instance, single-digit subtraction activates the intraparietal sulcus, among other brain areas (Dehaene et al., 2003). Explicit spatial tasks, like mental rotation, also activate this area (Carpenter, Just, Keller, Eddy, & Thulborn, 1999). The colocation of function allowed Dehaene et al. to infer that subtraction depends on a spatially represented mental number line.³

Revisiting the Pragmatic Concerns

In the preceding review of scientific concerns, we found opportunities for new research questions of potential mutual interest to education researchers and neuroscientists. But it is unclear whether educational neuroscience can answer these questions. Earlier, we raised four pragmatic concerns. We revisit them here from a more optimistic vantage.

Opportunity 5. Costs: Educationally relevant neuroscience might attract additional research funding to education. The concern that neuroscience research will reduce the funding available to education research rests on two assumptions: that education and neuroscience have independent research agendas, and that funding for the two disciplines is jointly fixed. Under these assumptions, the increasing funding for neuroscience would necessarily result in decreasing funding for education research. This *cannibalization* model is shown in Figure 2. However, there are reasons to question both assumptions.

The defining claim of educational neuroscience is that the two disciplines that constitute it are not independent. Rather, they are interdependent, and there exist research questions of interest to both communities. If this claim is correct, it suggests an alternate model wherein a portion of the funding for education and a portion of the funding for neuroscience might be redirected to studies that inform both educational practice and principles of brain function. For example, because federal grant proposals that promise social applications are ranked more highly than those that do not, it stands to reason that neuroscience grant proposals on educational issues are more likely to be funded (Geake & Cooper, 2003)—and funded through neuroscience sources without cannibalizing educational sources.⁴ Under this *multidisciplinary sharing* model, also shown in Figure 2, the overall funding available for education research increases (although the funding available for conventional education research decreases).

It is also possible that education and neuroscience might *not* be locked in a zero-sum funding contest. If collaborations between education researchers and neuroscientists produce new and innovative research, additional funding may be attracted to

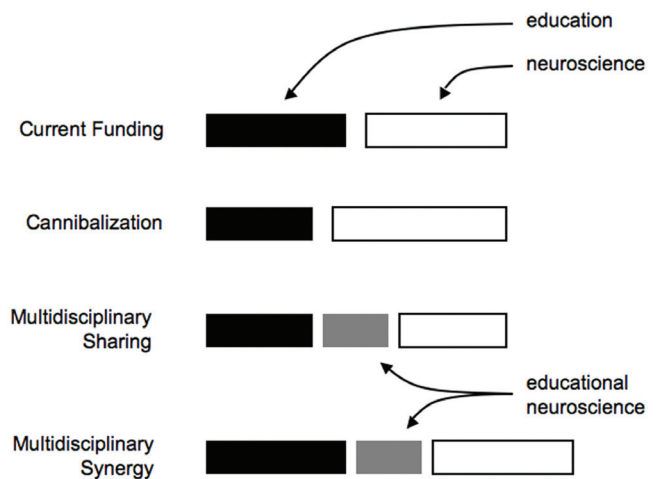


FIGURE 2. Possible funding models for educational neuroscience. The total funding for education research decreases under the cannibalization model, remains constant under the multidisciplinary sharing model, and increases under the multidisciplinary synergy model.

both disciplines. Under this *multidisciplinary synergy* model (Figure 2), the current funding level for conventional education research remains unchanged and is supplemented by funding for new studies that include neuroscience components. If the 1990s were “The Decade of the Brain,” perhaps the 2010s will be “The Decade of Educating the Brain.”

Opportunity 6. Timing: There are already signs of success. A number of educational neuroscience projects are already under way. The most mature example is in early reading skills. The initial research used fMRI to identify differences in the language networks of typically and atypically developing children (Schlaggar & McCandliss, 2007). More recent research is making three important contributions: (a) documenting the impact of particular educational interventions, (b) extending the initial research to languages other than English, and (c) finding that some differences between typical and atypical development also help to explain individual differences within the “normal range.”

A number of neuroscience studies have examined the impact of remediation programs for dyslexia developed by education researchers (Aylward et al., 2003; Shaywitz et al., 2004; Simos et al., 2002; Temple et al., 2000; Temple et al., 2003). In a representative study, Eden et al. (2004) used fMRI to identify the different brain networks recruited by typical readers and those with dyslexia, shown in the left and middle panels of Figure 3, respectively. The dyslexic readers showed reduced activation in areas (including the supramarginal gyrus) that have been implicated in the mapping of orthography (the shape of words) to phonology (the sound of words). The dyslexic readers were then run through a program that education researchers had developed for remediating phonological difficulties. Successful remediation was associated with increasing activation in these areas, shown in the right panel of Figure 3. In other words, the brain networks of successfully remediated dyslexic readers came to resemble those of typical readers. The partnership between education and neuroscience

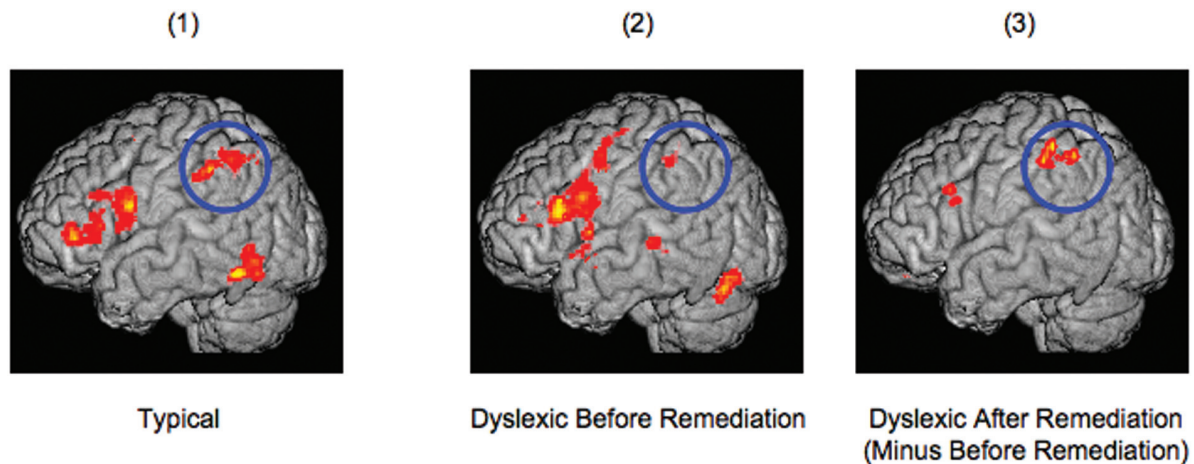


FIGURE 3. *Remediation of dyslexia at the level of brain function.* (1) Left-hemisphere areas active in typical readers. (2) Before remediation, dyslexic readers show reduced activation in the supramarginal gyrus. (3) Remediation results in increased recruitment of the supramarginal gyrus (as well as other areas). From Figures 1 and 3 of “Neural Changes Following Remediation in Adult Developmental Dyslexia,” by G. F. Eden et al., 2004, *Neuron*, 44, pp. 411–422. Copyright 2004 by Cell Press. Adapted with permission.

in this study informs our understanding of typical reading development, of reading disability, and of why some interventions are effective for some individuals. One might argue that whatever information emerged from this study, the important educational work had already been done—and the remediation programs already existed. But this argument overlooks the benefits of a neuroscience explanation of *why* such programs work. For example, the neuroscience explanation has led to new research that examines the early roots of dyslexia in infants (McCandliss & Wolmetz, 2004).

Another important contribution of neuroscience research on dyslexia is to raise interesting new questions, such as whether the nature of the underlying deficit is the same across languages. Paulesu et al. (2001) used fMRI to study differences between typical and dyslexic readers of Italian, French, and English. Although these languages differ in many ways, the nature of the deficit is the same in all three: Dyslexic readers show reduced activation in the same brain areas in comparison with typical readers (including the superior temporal gyrus, which is adjacent to the areas where Eden et al., 2004, found reduced activation). The implication—untested to our knowledge—is that similar remediation programs should have similar effects across all three languages. In contrast to these three alphabetic languages, Chinese is a logographic language. Siok, Perfetti, Jin, and Tan (2004) found that typical Chinese readers recruit a network of brain areas (including the middle frontal gyrus) consistent with the increased visual attention demands of processing logographic words. Critically, the researchers found that dyslexic Chinese readers showed reduced activation in visual attention areas but not in the areas implicated in dyslexia for alphabetic languages. The hypothesis—again, untested to the best of our knowledge—is that logographic and alphabetic languages will require different remediation programs. It also raises the intriguing question of whether dyslexic readers in one language would be typical readers in another.

These lines of research are promising, and many see neuroscience as an important asset in the effort to diagnose and remediate

substantial learning difficulties (e.g., Butterworth, 2005; Shaywitz et al., 2004). But a quandary remains: If neuroscience research can inform educational questions only about atypical brains, and if atypical brains differ categorically from typical brains, then can neuroscience research ever inform educational questions about average people? Although it is true that neuroscience insights into education historically have followed from research on atypical brains, it is increasingly possible to observe subtle yet reliable individual differences within the “normal range.” The critical insight of these studies is that, in some cases, what appear to be categorical differences between typically and atypically developing children are better viewed as quantitative differences along a continuum.

Returning to the example of reading, it turns out that many of the characteristics that differentiate typical from dyslexic readers also differentiate *among* typical readers. Shaywitz et al. (2002) found a relationship between reading ability and brain activation that distinguished *between* dyslexic and nonimpaired children. They found the same relation when examining individual differences *within* the nonimpaired group. A similar continuity is emerging in studies of brain connectivity. Many topics of formal instruction depend on developing strong connections between brain areas. For example, reading requires connecting the visual areas that discern the shapes of letters with the phonological areas that sound them out. These connections are through long axons that collectively form white matter tracts. Niogi and McCandliss (2006) found white matter tract differences between reading-disabled and nondisabled children. But differences in white matter tract organization are also correlated with differences in standardized reading scores within the “normal range” (Beaulieu et al., 2005). These examples illustrate how research on atypical populations can provide a toehold to understanding the functional structure of the brain, and how subsequent research can illuminate the finer gradations of performance present in typically developing children. This work may ultimately inform educational efforts to adapt instruction to individual differences.

Opportunity 7. Control: Ask not what neuroscience can do for education, but what education can do for neuroscience. The relation between education researchers and neuroscientists is often viewed with an assumption of asymmetry: Neuroscience can inform education, but education has nothing to offer neuroscience. We believe this assumption is incorrect (cf. McCandliss, Kalchman, & Bryant, 2003). Education research has produced unique insights into the nature of complex cognition and its development—insights that are potentially of foundational importance to future neuroscience research.

One place where education can take a leading role is in providing guidance on future neuroscience research into complex forms of cognition. Early neuroimaging studies focused on simple forms of cognition such as perception and attention. Current experiments target more complex forms of cognition. Which phenomena will be the subject of future neuroimaging studies? This is a question that education researchers are poised to help answer (Byrnes & Fox, 1998; Mayer, 1998).

Many years of curriculum development, education research, and the wisdom of practice have led to an understanding of learning progressions in different content areas and how these progressions can go awry. This understanding can critically shape future neuroimaging studies of complex cognition. For example, recent fMRI studies address elementary forms of mathematical reasoning, such as enumeration (Piazza, Mechelli, Butterworth, & Price, 2002), comparison (Pinel, Piazza, Le Bihan, & Dehaene, 2004), place-value (Pinel, Dehaene, Rivière, & LeBihan, 2001), arithmetic (Dehaene et al., 2003), and estimation (Stanescu-Cosson et al., 2000). Researchers in mathematics education have been studying these topics for decades. They understand the underlying competencies, the trajectories along which the concepts are acquired, the obstacles to their acquisition, and the ways to route around these obstacles (Baroody & Dowker, 2003; Clements, Sarama, & DeBiase, 2004). Over the next few years, we anticipate that researchers in mathematics education and neuroscience will begin to collaborate on new studies of the development of elementary mathematical reasoning and its derailment in dyscalculia (Butterworth, 2003). This research promises to shape neuroscience as much as it shapes education.

Another likely contribution of education will involve the effort to understand how specific experiences give rise to brain circuitry during development. Important questions where education can contribute include the delineation of typical trajectories of subject-matter learning, the identification of experiences that are most important, and the determination of how individual differences influence the ability to form brain circuitry for learning in different content areas. Neuroscience has little groundwork for approaching these questions, whereas education research has already accumulated, and continues to accumulate, a significant empirical base. As researchers begin collaborating across disciplinary lines, there is already a large asymmetry of information in favor of education research.

Returning to the example of dyslexia, the study by Shaywitz et al. (2004) primarily examined the neural correlates of the impact of an educational intervention pioneered by Benita Blachman (Blachman, Schatschneider, Fletcher, & Clonan, 2003). This intervention was based on more than 20 years of education research on the cognitive aspects of reading disabilities and

how they can be best addressed through educational practice. Without the benefit of such research, neuroscience studies of reading deficits and their remediation would have been at a significant disadvantage and might have wound up recapitulating the same false starts and puzzlements that education researchers worked through 20 years ago. Instead, insights from educational and cognitive research pointed to phonological processing deficits as a primary hypothesis for the brain systems that were atypical in reading-disabled children. The educational work also provided paradigms for isolating and quantifying phonological processes and for providing intervention procedures that drove significant changes in reading development.

More generally, educational neuroscience is coming, with or without the consent of education researchers. Neuroscience is already encroaching on educational territory with studies of complex cognition and its development. Education researchers should not shy away from this challenge or inadvertently withhold their knowledge. Neuroscientists are unlikely to plow through hundreds of education articles. So without collaboration, neuroscientists are at risk of running naïve experiments informed by their personal experiences of how children come to learn content area skills and knowledge.

Opportunity 8. Payoffs: People like to think in terms of brains, and responsible reporting of cumulative results can help them. Neuromyths are problematic. However, their very existence tells us something important: People like to reason about brain function. Perhaps they find it easier to think with mental models of physical systems than with conceptual constructs such as schemas, goals, and working memory. Perhaps they find material causality the most compelling. Another, less attractive, possibility is that people feel comfortable abnegating responsibility for atypically developing children by blaming their behavioral problems on faulty wiring. Whatever the explanation, people appear to enjoy reasoning about behavior using models of the brain, however sketchy they may be. The question, then, is how to ensure that this reasoning is valid.

One answer is that we need more “plain text” translations of neuroscience findings that report clusters of studies in accessible ways without trying to sell them. One good example is the 2007 report *Understanding the Brain: The Birth of a Learning Science*, published by the Organisation for Economic Co-operation and Development.

A second answer is that inferences from neuroscience data to educational topics are more likely to be valid if they are interpolations, not extrapolations. It is dangerous to generalize too far outside the scope of neuroscience findings to formulate advice about how to teach a particular content area. It is safer to target content areas that have been the subject of many neuroscience studies using a variety of methods, tasks, and populations. The existing literature can then constrain inferences, lessening the likelihood of neuromyths.

As we saw above, reading is an example of a well-studied content area. Neuroscientists worked for years to identify the brain areas that activate in typical readers and, later, the subset of areas that fail to activate in dyslexic readers. These data constrained the choice and evaluation of remediation programs. Mathematics appears to be approaching the same point. There is currently a

large effort to document the neural bases of *dyscalculia*, the mathematical analog of dyslexia (Butterworth, 2005). There are a number of hypotheses regarding the cause of dyscalculia, including reduced working memory (Geary, 1993), impoverished semantic memory (Geary, Hamson, & Hoard, 2000), limited subitizing (Koontz & Berch, 1996), impaired numerical reasoning (Landerl, Bevan, & Butterworth, 2004), and a lack of focus on mathematically meaningful properties (Hannula, 2005). By contrasting typical and dyscalculic groups, fMRI studies are just beginning to identify the neural bases of dyscalculia (Kucian et al., 2006). This effort, in conjunction with studies on the effects of learning interventions, is likely to avoid neuromyths because it is constrained by a large and growing literature. By contrast, neuroscientists are just beginning to understand the neural bases of scientific reasoning (Fugelsang & Dunbar, 2005). To derive recommendations for science education from these initial studies would require extrapolation and therefore run the risk of creating neuromyths.

Conclusion

This article has consolidated a number of thoughts in the air about the perils and prospects for educational neuroscience and solidified them with examples of how neuroscience goes about its work. We first presented eight concerns about current attempts to connect education and neuroscience. We noted that even if the four scientific concerns—about the commensurability of the methods, data, theories, and philosophies of the two disciplines—can be surmounted in principle, the four pragmatic concerns suggest that doing so will be difficult in practice. We next revisited the eight concerns, this time finding examples from the neuroscience literature that indicate the potential for complementary research agendas. We argued that although the concerns represent a challenge to educational neuroscience, they also represent an opportunity for innovative new research.

Ultimately, the value of educational neuroscience is an empirical question. For those who believe this question to be worth engaging, we offer two reflections on taking action. The first is that bridging the divide that separates the education and neuroscience *disciplines* requires bridging the divide that separates the education and neuroscience *communities*. The second reflection is that we should remain cautious in our optimism. Education research and neuroscience can inform each other, but within limits, which we have yet to discover.

Suggestions for Improving Communication Between Education Researchers and Neuroscientists

The divide between the disciplines of education and neuroscience is also a divide between their respective research communities. Neuroscientists take simple behaviors (e.g., the process of comparing two numbers to determine which is greater) and try to understand them in terms of even simpler processes (e.g., the linking of number symbols to magnitudes) and their neural implementation. This can frustrate education researchers, who may regard such simple behaviors as vanishingly small pieces of a much larger puzzle. They wonder how these tidbits can inform broader questions, such as how to motivate and enculturate children into important symbol systems. In turn, educational

questions can befuddle neuroscientists, who view controlling “nuisance” factors as a prerequisite to asking questions that are informative about basic mechanisms. We propose two strategies for improving communication between the education and neuroscience communities.

Focus on domains, not on disciplines. One strategy is to stop putting forward our disciplines as the basis for our identities and instead to put forward the problems we study. Problems can serve as neutral ground and can anchor intellectual exchange. If one’s goal is to conduct research within mathematics education, for example, then it is natural to defend one’s discipline against incursions by neuroscientists and other outsiders. However, if one’s goal is to understand the development of multiplicative reasoning, then many disciplines potentially offer fruitful insights: mathematics education, to be sure, but also the history of mathematics, developmental and cognitive psychology, ethnography, neuroscience, and so on. When researchers identify themselves by the problems they study, then it is valuable to travel to foreign disciplines in search of new insights and to bring back souvenirs—new methods, data, and theories for answering the questions of one’s native discipline.

Focus on collaboration, not competition. Another strategy is for education researchers and neuroscientists to view themselves as collaborators, not competitors, in the pursuit of knowledge. This requires a commitment to working together. Genuine collaboration is more than parallel play or trading of results. It would be a mistake for education researchers to think that neuroscientists will want to run neuroimaging studies for them, just as it would be a mistake for neuroscientists to think that education researchers will want to collect baseline data on how children perform tasks of minimal ecological validity. It is critically important to formulate questions that have empirical and theoretical importance for both communities but that neither community could answer alone.

For example, during his postdoctoral training, one of the authors of the present article (Bruce McCandliss), who had studied the neuroscience of attention and brain plasticity in learning, collaborated with Isabel Beck, an expert in reading education. They found common ground through reading curriculum materials that Beck had developed throughout her career (Beck & Hamilton, 1996). Working together (and with colleagues at the Learning Research and Development Center) on the hypothesis that this approach helped children to focus attention on the specific connections between letter and sound combinations within words, they created a software program, The Reading Works. They developed a research collaboration that provided insights useful within each of their disciplines, while building a potential corridor of explanation between education and neuroscience. For example, a behavioral study tested the efficacy of the program for children with reading disabilities (McCandliss, Beck, Sandak, & Perfetti, 2003). A neural network model of developmental dyslexia was constructed that provided a mechanistic explanation for the success of the program (Harm, McCandliss, & Seidenberg, 2003). The program is currently being evaluated in a school-based randomized control study of poorly performing elementary school children (versus practice-as-usual tutoring), combined with a before-after neuroimaging study to test whether its effectiveness is

linked to changes in activation patterns across brain regions engaged in phonological and visual processes during decoding (McCandliss, 2007).

Cautious Optimism

We agree with other commentators (Ansari & Coch, 2006; Byrnes & Fox, 1998; Geake & Cooper, 2003; Goswami, 2006; Petitto & Dunbar, in press) who see reasons to be optimistic about the future of educational neuroscience. Nevertheless, the potential for collaboration is not unbounded, and insights will take time to develop.

One reason for caution is that the scope of educational neuroscience is not yet clear. The field is still in its infancy, and we do not know its limits. One reviewer of an earlier version of this manuscript asked us to draw a hard line between the disciplines, indicating which aspects of education should remain untouched by neuroscience—with the implication that these aspects should also retain protected funding. We are not willing to do this. Clearly, some educational questions are far removed from neuroscience, such as policy decisions on drawing district boundaries; but at a theoretical level, it seems premature to say that one line of research could never have relevance for another. Multidisciplinary research efforts often spawn new explanatory tools that dissolve old theoretical boundaries. We are unwilling to speculate about the limitations of educational neuroscience on the basis of current theoretical divisions, for example, between cultural and psychological approaches to learning.

Nevertheless, we have seen that neuroscience treats the motivational, cognitive, social, and emotional dimensions of learning as integral (Montague et al., 2006). We have seen that neuroscience research sheds light on cross-cultural differences in reading and mathematical reasoning (Siok et al., 2004; Tang et al., 2006). Studies of the neural correlates of experiencing violence in video games are beginning to appear (e.g., Weber, Ritterfeld, & Mathiak, 2006). As these examples suggest, the ultimate scope of educational neuroscience is an empirical question.

Another reason to be cautious about educational neuroscience is that launching multidisciplinary research is difficult, regardless of the disciplines involved. Educating (and learning from) one's colleagues about the insights and methods of a remote discipline requires commitment. In our experience, it takes at least a year of sustained interaction before such a process begins to generate tractable research questions of genuine interest to all involved. A joint multiyear grant is one way to sustain the process during the initial stages; working in a multidisciplinary center is another. In any case, it is important to ask repeatedly, "Would this finding be interesting to you?" and "Why is that finding interesting to you?"

The payoffs of educational neuroscience will likely be modest for the first generation of collaborators. Senior researchers have the security to foster interdisciplinary work, but they do not have the time (or perhaps the willpower) to earn the equivalent of a second doctorate and make a name for themselves in a new field. The big payoffs likely await the next generation of scholars, who will be intrigued by the small successes of the next few years and will go on to develop truly multidisciplinary identities and research programs that bridge from brain to behavior to the problems of education.

We end with a final reminder: Education is not neuroscience, and neuroscience is not education. Each discipline addresses a broad range of research questions using a variety of methods. The challenge is to identify the questions and methods that usefully overlap. At present, neuroscience has little to say about the social construction of inequity, and education has little to say about the hemodynamic response function. Educational neuroscience will need to mind these and other gaps—but it need not be defined by them.

NOTES

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¹Researchers have recently developed protocols for scanning children that involve familiarization in a mock scanner. As children watch DVDs or play games, they are slowly acclimated to the environment of the scanner and its requirements for effective measurement. These protocols are helpful, although there is still a high rate of data loss when scanners are used with children.

²This identification process is supported by electronic databases such as BrainMap (Laird, Lancaster, & Fox, 2005) and statistical tools such as meta-analysis (Wager, Lindquist, & Kaplan, 2007).

³One caveat is in order here. Neurons aggregate into functional circuits at a spatial level of organization smaller than the resolution of fMRI. Thus it is not necessarily the case that, just because two tasks activate the same brain area, the same populations of neurons and therefore the same functional circuitry are being recruited. Nevertheless, overlapping patterns of brain activation provide an entry point for investigating the potential of shared function. Methods such as fMRI-adaptation can resolve some of this ambiguity (Grill-Spector & Malach, 2001).

⁴In this context, it is important to realize that neuroscience is a much larger academic discipline than education. In 2007, approximately 32,000 people attended the annual meeting of the Society for Neuroscience, whereas approximately 16,000 people attended the annual meeting of the American Educational Research Association.

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