Is Neuroscience a Learning Science?

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Abstract: Should education and neuroscience be connected? We review eight arguments against and eight arguments for connecting the two disciplines. We conclude that ultimately, whether education and neuroscience have anything to offer one another is an empirical question – one that is worth engaging.

Introduction

In an early appraisal of the prospects for connecting education and neuroscience, Bruer (1997) pronounced it "a bridge too far." This was particularly noteworthy because at the time, Bruer was director of the McDonnell Foundation and was actively funding research in both disciplines. Even though it was in his best interests to find connections between them, he found few. Eight years have passed since Bruer's cautionary evaluation. In the interim, the maturation of functional Magnetic Resonance Imaging (fMRI) has brought an exponential increase in the data on the neural bases of cognition, including those complex forms most relevant to education, such as language comprehension and mathematical reasoning. The time has come once again to ask whether education and neuroscience should be connected.

This question is addressed in two complementary sections. The first offers eight reasons against bridging between education and neuroscience. The second section counters these with eight reasons for bridging between the two disciplines. To preview our conclusions, we believe that reasoning against and reasoning for will only get us so far, and that it is an empirical question whether combining education and neuroscience will yield important empirical, theoretical, and practical advancements. Furthermore, we believe this is an experiment worth undertaking, and that its success will depend critically on educational researchers and neuroscientists collaborating across disciplinary boundaries.

Reasons Against Connecting Education and Neuroscience

A number of reasons against connecting education and neuroscience have appeared in the literature and have been shared with us in conversations with colleagues. The issues are real, although space constraints prohibit us from drawing all implications and listing supporting examples here.

Scientific: The Differences Between Brain and Behavioral Data

(1) ***Neuroscience data will never have anything to offer education.*** Even if the mind is in the brain, and therefore cognition is the product of neural computation, this does not mean that the particular neural locations of cognitive competencies are relevant for educational researchers, whose goal is to foster these competencies in children (Mayer, 1998, p. 394). For example, does it matter to curricula for teaching sentence structure whether syntax is localized in left Inferior Frontal Gyrus (IFG), the hippocampus, or striate cortex? Does this inform the pedagogy in any way? And of course, the mind as we find it in the classroom is *not* just in the brain. Behavior is profoundly shaped by context. Neuroscience methods, however, demand highly constrained and artificial contexts. For example, in fMRI experiments, participants lie inside a large and noisy cylindrical magnet and, in the vast majority of cognitive paradigms, are shown projected screen images and only permitted to press a button, which they must do for hundreds of trials to generate signals that rise statistically above the noise. In contrast, when collecting behavioral data in educational settings, context becomes the most important variable because it is what can be manipulated to change large-scale behaviors.

Philosophical: The Differences in Vocabularies and their Reduction

(2) ***The vocabularies of education and neuroscience are incommensurable.*** Education and neuroscience are different disciplines, and have evolved vocabularies appropriate for the different phenomena they study. The vocabulary of education belongs to social science and includes *mental* terms like meaning and understanding. The vocabulary of neuroscience belongs to biological science and includes *material* terms like hemodynamic response and neural pathway. It is possible that these vocabularies are fundamentally incommensurable because one is about mind and one is about body. The Cartesian dualism will preclude any dialogue between the disciplines (Byrnes & Fox, 1998, p. 299). Moreover, even if the vocabulary of education could be reduced (i.e., translated) to that of neuroscience, there would be no value in substituting neuroscience terms for proven educational terms (Byrnes & Fox, 1998, p. 299). For example, consider a child having difficulty mastering the indirect object construction. Nothing is gained by calling this "syntactic deficit" a "left IFG deficit" instead.

(3) ***Even if education can be reduced to neuroscience, reductionism is a disservice to those we educate.*** The significant parameters of education occur at the level of classroom dynamics, and these cannot be adequately reduced to brain function. The norms that regulate classroom interaction, for example, cannot be described as patterns of activations. Moreover, even if we could reduce the whole of education to neuroscience, this would not help pedagogy (just as reducing education to physics – translating educational theories into the language of fermions and bosons – would not help either). In fact, given the cumbersome nature of the lower-level terminology, the more likely consequence would be negative. We would lose sight of the lives we educate, because the reduction would force us to consider educationally-irrelevant details such as the statistics of neural spike trains.

Pragmatic: The Timeline of Research Developments

(4) ***We don't know enough about how the brain works at the current time to inform any educational topics.*** The study of how the brain performs the complex forms of cognition of greatest relevance to education is still in its infancy. We do not yet know enough about the neural localization of language comprehension, mathematical problem solving, or scientific reasoning to inform reading, mathematics, or science education (Bruer, 1997, p. 4). Cognitive neuroimaging is, after all, a relatively recent development. The number of neuroimaging studies of cognition has exploded over the past fifteen years. It still remains for cognitive neuroscientists to make sense of these data and to deliver theories of brain function at a level of abstraction appropriate for educational behaviors and changes.

Historical: Dissemination of Findings

(5) ***Too often in the past, neuroscience findings have become <u>neuromyths</u>.*** Several times in the recent past, neuroscience findings have been inappropriately extrapolated into educational advice of dubious value (Goswami, 2004, p. 11). For example, based on animal studies of synaptogenesis, critical periods, and environmental enrichment, claims have been made regarding the "neuroscientifically appropriate" sequencing of instruction for young children (Bruer, 1997). One still hears educational researchers speaking of the left and right hemispheres as if they are distinct organs with nothing in common. Educational researchers become frustrated when neuroscientists fail to derive from their laboratory research clear lessons that can be straightforwardly transferred to the classroom. Conversely, neuroscientists become frustrated when the precision and scope of their work are ignored in over-zealous educational applications, however well-intentioned. The general lesson appears to be that neuroscience findings must be unduly stretched, distorted, and over-simplified to make contact with educational topics.

Institutional: Requirements for Training Teachers

(6) ***We cannot expect teachers to master neuroscience.*** Teachers are already asked to master multiple disciplines during their training: education, cognitive and developmental psychology, content domains, cultural analysis, etc. They do not have the additional time to learn enough about brain function to make sense of the neuroscience literature. Brain anatomy alone requires weeks (if not months) of sustained study. For example, different papers refer to the same brain tissue as Broca's area, left IFG, pars triangularis, Brodmann area 45, and voxel (–44, 3, 29) in Talairach space. Teachers-in-training do not have the time to master these multiple and redundant brain geographies, let alone the details of the networks of brain areas that implement different cognitive competencies.

Financial: The Cost of Research

(7) ***It is too expensive to conduct neuroimaging studies in education.*** The research funding available for educational research is fixed (or perhaps even shrinking). It costs hundreds of dollars per hour to run participants in neuroimaging experiments versus a few dollars per hour to run them in behavioral classroom experiments. A costbenefit analysis does not support spending two orders of magnitude more money on neuroscience studies, and thereby reducing educational studies in proportion.

Disciplinary: Ownership of the Research Agenda

(8) ***If education cedes control to neuroscience, it will never get it back.*** In the "decade of the brain" just ended, neuroscience exploded. The first casualty was cognitive psychology, which went from (a) a standalone discipline known for exquisite behavioral demonstrations and decompositions of human competencies to (b) an arm of neuroscience – so-called cognitive neuroscience. Debates in cognitive psychology increasingly turn on neuroimaging data, with behavioral data given short-shrift. A generation of cognitive psychologists has been rendered second-class citizens in their own discipline. Educational researchers will face a similar fate if neuroscience is allowed to enter.

Reasons for Connecting Education and Neuroscience

The eight reasons against connecting education and neuroscience, though compelling, do not constitute an ironclad case. Here, we present eight corresponding reasons for connecting the two disciplines.

Scientific: The Differences Between Brain and Behavioral Data

(1) ***Neuroscience data can be used to generate new educational hypotheses.*** Neuroscience data can be used to generate novel educational theories (Byrnes & Fox, 1998, p. 337). They are often counter-intuitive, and reveal different "joints" in cognition than are visible at the behavioral level. For example, neuroimaging studies find that the multiplication of one-digit numbers (4x2=?) activates brain areas where one would expect the "mental multiplication table" to be stored (i.e., angular and supramarginal gyrus). Surprisingly, subtraction exhibits a different pattern of activation, even though subtraction facts are also well-known. Specifically, the subtraction of one-digit numbers (4-2=?) activates areas known to perform visuospatial processing (i.e., intra-parietal sulcus and superior parietal lobule). One interpretation of this difference is that one-digit multiplication problems are solved by verbally retrieving the relevant arithmetic facts whereas single-digit subtraction problems are solved by constructing and scanning a "mental number line" (Dehaene, Piazza, Pinel, & Cohen, 2003). This *dissociation* at the brain level is invisible at the behavioral level, and demands new conceptions of multiplication and subtraction. One new hypothesis is that subtraction of natural numbers differs from multiplication in that it is open, not closed, and therefore requires use of a mental number line to check whether the result crosses zero into the range of negative numbers (2-4=?), whereas multiplication does not. In this way, counter-intuitive neuroscience results can force us to carve phenomena at different joints (e.g., whether a mathematical operation is open or closed) than we would expect based on the behavioral theories of education.

Although the contexts and behaviors permitted within fMRI experiments are restricted, it is still possible to examine the effects of context and complex behaviors. For example, participants can be separated into two conditions where they complete a month of lessons on a mathematical topic. In the 'memorization' condition, people can memorize the solutions to problems. In the 'hands-on' condition, people can work with physical manipulatives to learn the solutions to the problems. Participants in both conditions can learn to ceiling, so they are able to complete a set of 50 problems from memory. They can then be scanned during a posttest that includes two types of problems – those they memorized and new problems they have not studied. The patterns of brain activation should be different for the two conditions on the problems they have memorized, even though all participants should be able to solve these problems perfectly. Participants in the memorization condition should show activation in verbal (i.e., temporo-parietal) areas whereas participants in the hands-on condition should show activation in motor (i.e., fronto-parietal) areas. Moreover, when solving new problems, participants in the memorization condition should show diffuse activation and perform poorly, whereas those in the hands-on condition should recruit the same motor areas to successfully solve the problems. This would be true, even though their only overt behavior in the impoverished context of the scanner would be pressing a button to indicate their answers.

Philosophical: The Differences in Vocabularies and their Reduction

(2) ***Neuroscience may help resolve incommensurabilities in vocabulary.*** As neuroscience theories appear that address those cognitive competencies of greatest interest to education, there is every reason to believe that some will make contact with educational theories of how to teach those competencies (Byrnes & Fox, 1998, pp. 300, 329, 337). If one is skeptical of this claim, it is important to realize that pointing exclusively to the incommensurables between education and neuroscience is to ignore incommensurables within education itself. For example, within education, different methods are used to study the cognitive, motivational, and emotional dimensions of performance, and the results of such studies are published in different journals. By contrast, neuroscience provides a common biological vocabulary for describing cognitive, motivational, and emotional phenomena. In fact, the overlapping and intertwined networks of brain areas associated with these phenomena are a burgeoning area of research (as evidenced by journals such as *Cognitive, Affective, & Behavioral Neuroscience*). For this reason, neuroscience has the potential to overcome some of the incommensurabilities within education.

Educational researchers use constructs like ‘conceptual knowledge’, ‘understanding’, ‘hands-on learning’, ‘constructivist activities’, ‘exploration’, and ‘inquiry’ in ways that are not always consistent with one another. Neuroscience allows us to go beyond the vagueness of constructs and to also organize results in a place-based manner. A current push in some cognitive neuroscience journals is to require authors to provide a table of the brain coordinates that showed activation during a task. This permits other researchers to identify common patterns of activation across different studies, tasks and constructs. In other words, rather than anchoring findings to ambiguous labels, they are anchored to precise locations. Another important development in cognitive neuroscience is the use of meta-analyses based on these tables. For example, the preceding finding that subtraction and multiplication activate different areas was found by analyzing the data from many different studies that varied on a number of dimensions (e.g., presentation mode), but that reported their results in a place-based manner (i.e., by brain coordinates).

(3) ***Reductionism in not bad if it is not <u>eliminative</u> reductionism.*** Eliminative materialism is the doctrine that neuroscience explanations should not just anchor, but replace educational explanations (Byrnes & Fox, 1998, p. 300). Except in large paradigm shifts, eliminative reductionism has not been the natural course of events. For example, neuroscience has embraced the terminology and findings of information processing *and* behaviorism. Biology provides a nice example of maintaining levels of analysis within a reductionist paradigm. Biology attempts to make a corridor of explanation from cellular processes to ecosystems. The explanations at each level are consistent with one another, but they cannot *a priori* predict one level from the other. Similarly, reduction from education to neuroscience does not presuppose elimination.

At the same time, it is naïve to believe that all educational phenomena, such as the norms of classroom discussion, will be addressable by neuroscience in the near future. In connecting the disciplines, we need to select cross-over regions carefully. One general principle is that when neuroscience has reduced a complex cognitive ability to a set of component processes and mapped each process to a distinct brain area, then remediation programs for the ability can be developed that strengthen each component process in turn. An example of this principle is given in the next section.

Pragmatic: The Timeline of Research Developments

(4) ***There are already signs of success.*** A number of educational topics have already been informed, or are in the process of being informed, by neuroscience data. The canonical example comes from reading (Byrnes & Fox, 1998, p. 322; Goswami, 2004, 7-8). Neuroscience identified the brain areas associated with reading disability, mapped them to the processing of sounds corresponding to letters, and was poised to investigate the role of experience in modifying activity in these areas. At this point, education provided tried-and-true (though perhaps theoretically limited) methods for remediating phonological difficulties in kids. This partnership between neuroscience and education has informed our understanding of normal reading development, reading disability, and why some interventions are effective for some individuals, and is expanding in interesting ways, such as new investigations that leverage these insights to investigate the early roots of dyslexia in infants (McCandliss & Wolmetz, 2004). Another example comes from mathematics education, where neuroscience research is informing the design of diagnostic tests and remedial programs for dyscalculia, i.e., problems in reasoning mathematically (Landerl, Bevan, & Butterworth, 2004). On the horizon is guidance for the teaching of second languages from the neuroscience data on bilingual language comprehension (Petitto & Dunbar, 2004, pp. 2-10). And if education is defined broadly enough to include the special populations that are increasingly being mainstreamed into regular classrooms, then it will surely be informed by the rapidly expanding neuroscience literature on ADHD and Asperger’s syndrome (Petitto & Dunbar, 2004, p. 1).

Historical: Dissemination of Findings

(5) ***Although neuroscience findings cannot be safely <u>extrapolated</u> to make contact with educational topics, they can be <u>interpolated</u>.*** Although neuroscience findings have been inappropriately applied to educational topics in the past (Bruer, 1997, pp. 4-5), this does not have to be the case in the future (Geake & Cooper, 2003, p. 13). The lesson here is not that neuroscience has no implications for education, but rather that useful implications are more likely to be drawn when neuroscience data are interpolated, not extrapolated. To continue the example of the previous section, it was not until neuroscience had painstakingly documented the brain areas responsible for the letter-sound mapping that a bridge could be built to educational research on dyslexia. As our understanding of the neural bases of other forms of complex cognition grows, so will the likelihood that this understanding will make contact with educational topics in a way that results in new pedagogy.

Institutional: Requirements for Training Teachers

(6) ***Properly abstracted findings from neuroscience might be easier for teachers than current models.*** The fact that teachers and the public at large readily embrace neuroscience theories suggests they might be more comfortable models with which to reason about cognition. The alternative we favor is that people are especially facile with spatial models of phenomena. Educational theories are abstract, typically taking the form of linguistic assertions. As a result, it is difficult to imagine how their components interact over time. Neuroscience theories, by comparison, make heavy use of spatial models – visual depictions of brain areas, the pathways that connect them, and their engagement during task performance. These models might be a powerful way for would-be-teachers to organize their understanding of cognition – which is typically presented piecemeal on a domain-by-domain basis – into a coherent whole. The challenge for teacher training, then, is to exploit the affordances of the spatial models of neuroscience to distill the literature in a way that is comprehensible to interested novices.

Although neuroscience is a complex subject, there are several ways to make it tractable for teachers-in-training. One is to focus on those aspects of brain function – learning and memory – most relevant for education, which is concerned with the acquisition, organization, and application of knowledge (Geake & Cooper, 2003, p. 14; Goswami, 2004, p. 1). Another strategy is for education to adopt the same stance towards neuroscience as medicine does toward biological science. We do not expect doctors to conduct research in biological science, but we do expect them to make sense of its literature. Analogously, the goal should not be to turn teachers into neuroscientists, but rather to prepare them to be intelligent consumers of reviews of the neuroscience literature.

Financial: The Cost of Research

(7) ***Educationally-relevant neuroscience will bring more money into educational research.*** That neuroimaging experiments are more expensive than behavioral experiments on a participant-by-participant basis is a problem only if we assume that educational funding is fixed. There are two reasons why this assumption is likely to be incorrect. The first is that, generally speaking, scientific grant proposals that promise social applications are ranked more highly than those that do not. In particular, neuroscience grant proposals are more likely to be funded if their results are relevant for education (Geake & Cooper, 2003, p. 17). Therefore, if educational researchers partner with neuroscientists on projects of mutual interest, these projects can be supported by neuroscience funding without cannibalizing educational funding. The second reason is that if education and neuroscience prove to be a fecund combination, this will attract new funding for all educational research. If the 1990s was the decade of the brain, then perhaps the 2010s will be the decade of the educable brain.

Disciplinary: Ownership of the Research Agenda

(8) ***Ask not what neuroscience can do for education, but what education can do for neuroscience.*** A common assumption in discussions about the relation between education and neuroscience is that influence runs in only one direction: neuroscience can inform education, but education has nothing to offer neuroscience. This assumption is incorrect. Education is well-positioned to make important contributions to neuroscience (McCandliss, Kalchman, & Bryant, 2003). Early neuroimaging studies targeted low-level forms of cognition, such as visual search. Current neuroimaging studies are targeting higher-level forms of cognition, such as language comprehension and mathematical reasoning. What phenomena will the next generation of neuroimaging studies target? One place to look is education (Byrnes & Fox, 1998, p. 333; Mayer, 1998, p. 395). Educational researchers have documented and analyzed the acquisition of complex forms of cognition. These analyses can contribute to the framing of the next questions for neuroscience to address. For example, neuroscientists are currently documenting the neural bases of mathematical competencies such as enumeration, magnitude comparison, estimation, arithmetic, and place-value. They are poised to connect with math educators, who have been researching these topics for many decades. Math educators have invented representations and designed activities and instructional sequences to foster their development. They have documented the misconceptions and errors that arise and developed appropriate remediation strategies. Over the next few years, we expect these two research communities to cross-pollinate and the result to be a better understanding of the development of mathematical competence during the early elementary grades (and its derailment in dyscalculia).

Conclusion

We conclude with three observations that have been useful to us in thinking about research at the border between education and neuroscience.

Domains, not Disciplines

There exists a natural tension between disciplines that must be resolved for interdisciplinary research is to occur. One way to do this is to stop focusing on the different disciplines from which we come and start focusing on the common domains which we are interested in studying. If one's goal is to conduct research within math 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 instead to understand the nature of mathematical reasoning, then many disciplines potentially offer insights: the history of mathematics, the development of mathematical cognition, the mathematical abilities of other species, neuroimaging studies of normal young adults, neuropsychological studies of patients with brain lesions – and of course the math education literature. When we define ourselves by the domains we study, then other disciplines become useful sources of information.

Collaboration, not Competition

Educational researchers and neuroscientists do not have to view themselves as competitors for the same knowledge. It is more fruitful for them to view themselves as collaborators (McCandliss et al., 2003). This is particularly true in light of the first observation: that educational researchers and neuroscientists should focus on common domains rather than disciplinary differences. Such collaborations can potentially leverage the strengths of each discipline's methods and theoretical frameworks.

An Empirical Matter, not a Logical Matter

Ultimately, the relation between education and neuroscience is an empirical matter (Mayer, 1998). Logical arguments that neuroscience should be ignored and counter-arguments that it should be embraced are moot in the long run. The question is whether the collaborative research of educational researchers and neuroscientists on domains of mutual interest yields interesting new insights. We believe this question is worth engaging.

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