How to Build Educational Neuroscience: Two Approaches with Concrete Instances

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ABSTRACT

Educational neuroscience is an emerging discipline, but it is not a uniform endeavor. There are

different ways for it to make progress. We describe two broad approaches, which we

agnostically label Culture A and Culture B. Culture A is currently the more frequent approach.

It relies on individual differences to advance the science with a special emphasis on solving the

challenges faced by learners with special needs. Culture B is less common. It examines the

effects of contextual variables on typical learners to make headway at solving theoretical

problems in education and improving general instruction. Both are valuable and both seek to

improve education. By describing their differences, along with concrete examples of their logic,

findings, and cultures of work, we hope to help both neuroscientists and educators answer a key

question about one another's work, "Why do they find that worth doing?"

INTRODUCTION

There has been substantial theorizing on the wisdom of bridging neuroscience and the social sciences including economics (Camerer, Loewenstein, & Prelec, 2005), communications (Anderson, 2006), and political science (McDermott, 2004). The same is true of education (e.g., Ansari & Coch, 2006; Bruer, 1997; Goswami, 2006; Varma, McCandliss, & Schwartz, 2008). There are many important issues. For example, in education, biology is an aspect of the child, whereas in neuroscience, the child is an aspect of biology. Nevertheless, this article does not consider whether neuroscience should bridge into education – it already has. Instead, we address the more practical question of how the bridges should be made. What kinds of collaborations can see this work through?

Educational neuroscience is often characterized with a stepping stone metaphor. For example, the stones might be: biology <-> neuroscience <-> cognitive neuroscience <-> psychology <-> educational research <-> teaching. The stepping stone metaphor focuses on the flow of information from discipline to discipline. However, when thinking about how to foster effective interdisciplinary collaboration between individuals, we find it generative to think in cultural terms, rather than disciplinary ones. In this paper, we propose two complementary educational neuroscience approaches. Culture A is currently the dominant approach. It has generally been led by behavioral neuroscientists who look to education for topics and potential applications of their research. Less common, Culture B starts with educational researchers looking to behavioral neuroscientists to help solve broad theoretical problems in education. Major differences between these cultures are summarized in Table 1.

Table 1. Different Approaches towards Applying Neuroscience to Education.

	Culture A	Culture B
Initiators of Research:	Behavioral Neuroscientists	Educational Researchers
Phenomena of Study:	Biology of Individual Differences	Contexts of Typical Learners
Desired Educational Outcomes:	Solve Hard Specific Practical Problems	Solve Hard General Theoretical Problems
Collaborative Goals:	Make Incremental Progress	Investigate Novel Phenomena
Translation to Practice:	Educators as Implementers	Educators as Interpreters

We do not propose that one approach is better than another. We need both. Rather, we want to delineate reasons for including Culture B within the educational neuroscience portfolio. For example, in most universities, educational researchers are the people who train prospective teachers. Involving educational researchers in educational neuroscience from the outset means they will be able to think about its strengths, weaknesses, implications, and future possibilities. They can then pass this on to teachers-in-training. An alternative is to treat educational researchers as the recipients of packaged prescriptions and facts. This runs the risk of alienating the very people who are responsible for producing informed and high-quality classroom teachers

The paper is organized around Table 1. As we discuss each entry, we present examples and details that may illuminate the promise of each culture and the nature of the work. We hope to clarify what is currently happening in educational neuroscience in a way that helps both the behavioral neuroscientist and educational researcher understand why (and how) the other does

what they do. Dismissiveness is the enemy of innovation, and it is important to be able to

answer the question, "Why is that interesting to them?"
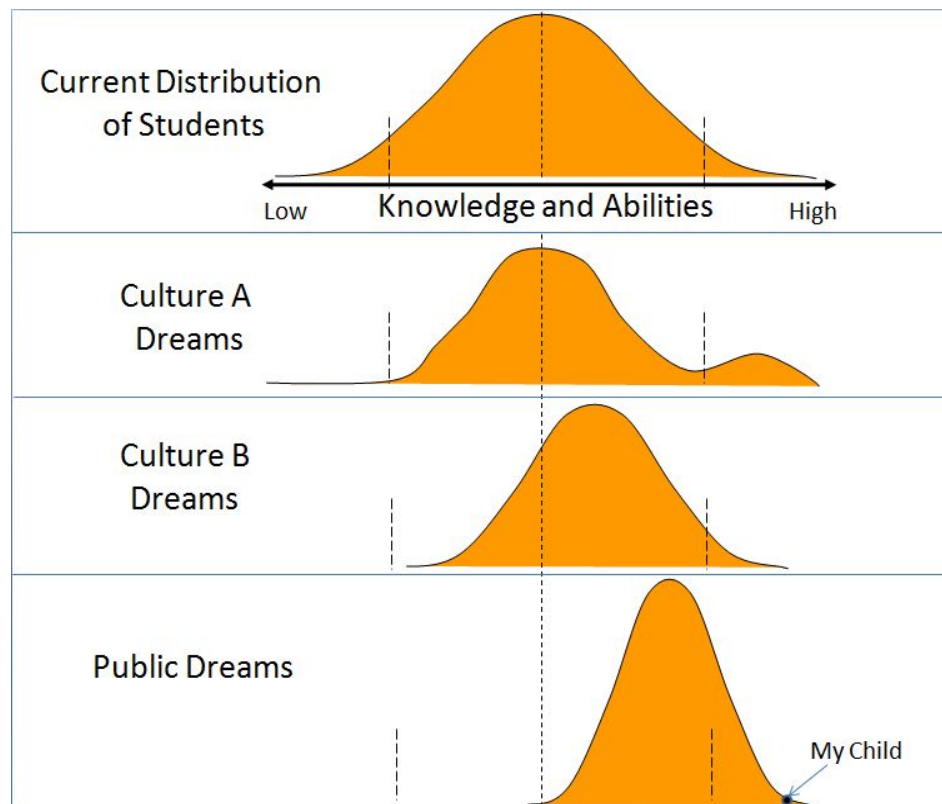
Figure 1. How Stakeholders Envision the Social Benefits of Educational Neuroscience.

PHENOMENA OF STUDY

Figure 1 contrasts the phenomena of interest for Cultures A and B. The top of the figure

shows a fictitious distribution of the student population. It is normally distributed with the

majority of students near average. Behavioral neuroscientists, who anchor Culture A, tend to

focus on the tails of the distribution; namely, children (and adults) with clinical problems or exceptional abilities (e.g., Gabrieli, 2009; Goswami, 2006; O'Boyle and Gill, 1998, Menon et al., 2000). A theoretical interest that can be addressed by contrasting typically and atypically functioning brains often drives Culture A, but ideally, it can also lead to the practical application of neuroscientific theories for moving the tails of the distribution. In contrast, educational researchers who anchor Culture B tend to focus on instruction with the goal of improving the average and ideally reducing the achievement gap. Their aim is to move the whole distribution rightward while decreasing the spread. These differences in interests have implications for the nature of the work.

Culture A: Explaining Individual Differences in Behavior and Learning

The dominant approach to educational neuroscience focuses on the study of pre-existing individual differences. Large behavioral differences increase the chances of finding brain structures and functions responsible for those differences. One example comes from the work of Tsang et al. (2009). In this study, students completed approximate addition problems. They saw a prompt such as "27+14," and their task was to choose whether "40" or "60" was closer to the answer. The students exhibited reliable individual differences in accuracy. What might explain these differences?
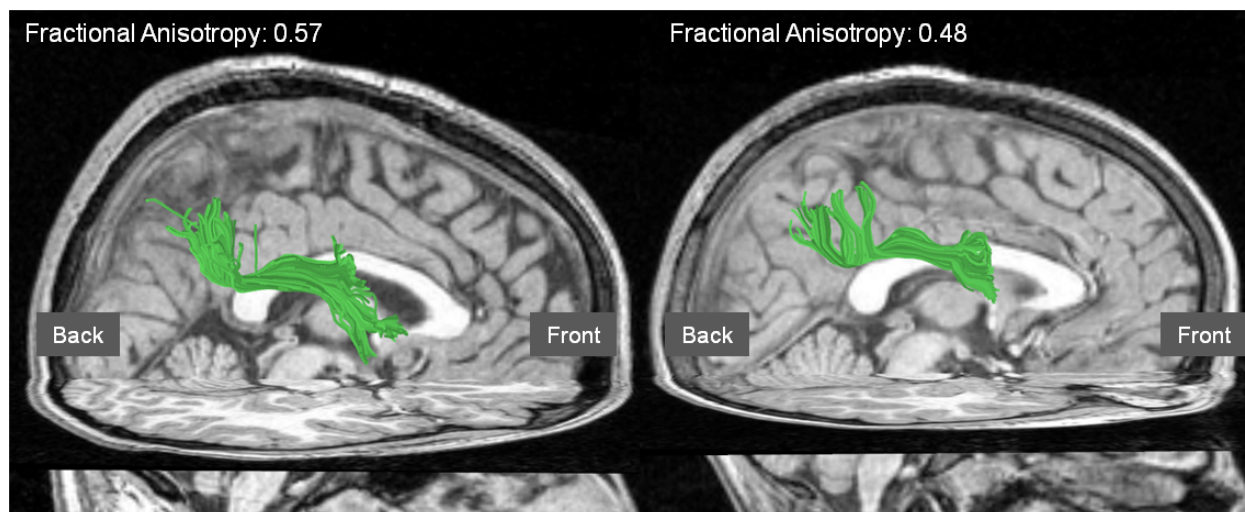
Figure 2. Individual Differences in the aSLF White Tract. The image shows selected white matter tracts (rendered in green) that connect two regions of the brain for two children. Fractional Anisotropy is a measure of tract coherence. In this study, the measure of coherence was taken near the center of the tracts (not the ends). Children with more coherent (well-organized) tracts did better at an approximate addition task.

From a cognitive perspective, there are several possible explanations. For example, students had not learned their math facts, or perhaps, they had a poor schema for handling multi-digit addition. Neuroscience explanations, on the other hand, focus on biological accounts of the differences. In this study, the researchers had the students complete a brain scan after doing the addition problems. The scan, a type of Magnetic Resonance Imaging (MRI), measured the structure of the brain's white matter. The white matter is responsible for transporting signals between brain regions. For this study, the focus was on the fibers that connect two regions that are active during approximate addition. Figure 2 contrasts the relevant pathways for two children. Children with more coherent (well-organized) fiber paths near the center of the tracts lengths did better at the approximate arithmetic task. Even after controlling for general factors like age and IQ, the quality of this pathway, and not others, correlated with performance.

The research did not determine why children had more or less coherent white matter in

this tract. Instead, it relied on pre-existing individual differences. Nevertheless, the example hints at the biological nature of explanation in brain science (behavior explained by physical connections rather than psychological constructs), and how it capitalizes on individual differences to do its work.

Most Culture A research capitalizes on larger individual differences than the Tsang et al (2009) study. The focus is often on children and adults with clinical-level difficulties compared to the average population. This includes significant research on dyslexia (e.g., Goswami, 2009), dyscalculia (e.g., Butterworth, 2005), social disorders (e.g., Baron-Cohen & Belmonte, 2005), and attention difficulties (e.g., Castellanos et. al, 2006). Focusing on clinical problems makes a good deal of sense. For example, if people with a specific lack of competence commonly show brain differences in a particular region compared to average people, then this creates a strong warrant that the brain region is involved in the competence. The clinical focus also has historical basis. The field of neuroscience has its roots in medicine (D'Amato, 2005), and the earliest studies concentrated on people with serious brain abnormalities, such as lesions, and their concurrent serious behavioral abnormalities. Additionally, in the United States, federal support largely came from the National Institutes of Health (Dorsey et. al, 2006), increasing the push toward solving clinical problems. Because education often reveals performance difficulties even after sustained opportunities to learn, it can become useful territory for finding and investigating clinical problems.

One of the exciting outcomes from the clinical approach is the development of brain assessments that can predict dysfunction before it has had a chance to interact with learning. For example, very young children with brain abnormalities in specific regions are likely to have

difficulties learning to read as they grow older (Gabrieli, 2009; Molfese, 2000). As a simple

example of why brain research can detect brain responses before behavioral manifestation, Kuhl

et. al. (2008) used electroencephalography (EEG) to measure the electrical activity of infants'

brains as they listened to speech. (EEG measures brain activity by placing electrical pickups on

the scalp.) Kuhl was able to determine that exposure to a specific language influenced the

infants' abilities to discriminate language-specific sounds well before they could speak ("ta"

versus "pa"). Speech depends on a complex coordination among many systems including the

vocal chords. Before infants have managed to put them all together, it is possible to measure

whether their brains are already learning differences in sound patterns. Measuring the precursors

of full-blown behavioral effects raises the hope of eventually developing and administering

treatments before children have had a chance to fall behind in learning. For example, one might

assess those children at risk for developing difficulties based on the heritability of dyslexia.

Cross-sectional comparison of children and adults is another method for capitalizing on

pre-existing differences (e.g., Ansari et al, 2005). These studies look at human development

regardless of specific experiential influences on development. For example, Rivera et al. (2005)

found that younger children solved simple math problems by recruiting the front regions of the

brain (3 + 2 = 6: True or False). These regions are often implicated in tasks that require high

degrees of conscious control. In contrast, older children and adults used more posterior regions

of the brain associated with memory retrieval. So, rather than thinking of skill development as

strengthening a single muscle, it appears that the skill "migrated" in the brain with the

development of expertise. Another pre-existing differences approach, which does take into

account large-grain differences in learning experiences, compares individuals from different

cultures, for example, by looking at the effects of different languages and writing systems (e.g., Tang et al., 2006).

By and large, the Culture A approach to educational neuroscience focuses on explaining pre-existing individual differences in terms of biological mechanisms. This differs from the interests of many educational researchers, who are more familiar with using instructional treatments to create differences.

Culture B: Explaining Instructional Effects for Average Students

In preparing this article, we canvassed a number of our educator colleagues, and Professor Aki Murata of Stanford neatly summarized the educator's question for neuroscience: "How can we teach so the brain will function in certain productive ways?" For many educational researchers, the dominant approach to research is to examine how contextual factors, such as instructional materials or classroom environments, affect learning outcomes for typical students. Context is what educators can control, so it makes sense that this is the starting point.

Culture B begins with the question of instructional effects rather than individual differences. While this is the less common approach, there are some examples of using instruction from the outset to examine brain organization and change (e.g., Delazer et al., 2005). One nice study comes from James (2010). This study used functional magnetic resonance imaging (fMRI) with 4-5 year old children. FMRI uses the same brain imaging machine as MRI, but it measures brain functioning rather than brain structure. When people complete different tasks, different parts of the grey matter (cortex) of the brain become more active and consume more energy. FMRI measures blood flow that supports this energy consumption. This so-called

BOLD response (blood oxygenation level dependence) serves as a proxy measure for neural activity.

James had children learn to recognize visual letters in one of two ways. In the visual recognition condition, the children named the letters. In the drawing condition, children copied the letters by hand. On a behavioral posttest, children in the drawing condition showed a modest advantage at recognizing letters. James also scanned the children using fMRI to see if the two treatments led to different patterns of neural activity. In the scanner, children simply looked at letters they had seen, novel pseudo-letters, and shapes. The children in the drawing condition showed increased activation in a region of the brain responsible for fine visual discriminations (anterior Fusiform Gyrus). The brain difference between the two treatments only occurred for the letters they had learned, and not for the shapes or pseudo letters. Thus, children who had completed the hands-on treatment showed task specific changes to a visual region of the brain.

This finding is interesting for neuroscience because motor activity may have changed a region that is dominated by visual processing. The finding is also interesting to educators who wonder about the value of hands-on activities. The study demonstrated an instructional method that makes the brain function in certain productive ways, just as our colleague had asked. At the same time, researchers in culture B need to be careful to remember that demonstrating a specific brain mechanism through instruction does not guarantee that the particular instructional intervention engages the best mechanisms possible. For example, Gibson (1969) reported that visually contrasting letter-like symbols side-by-side led to better recognition than copying them back in the 60's. In summary, Culture B often uses contextual manipulations including instruction to probe the nature of the brain, and ideally, it is also possible to consider the

effectiveness of these manipulations for achieving desirable educational outcomes.

The Logic of Inquiry in Culture A and Culture B

Culture A capitalizes on variability across individuals to accomplish its science. Culture B creates contextual variability to support its science. These differences influence the logic of inquiry. Culture A's strength methodologically and inferentially is connecting biological mechanisms and behavior. The research often focuses on how different behaviors manifest in the brain. For example, what are the brain differences between poor and good readers when they see versus hear words? By studying correlations between brain activity and behavior, researchers can begin to hypothesize about how changes in the brain might lead to changes in behavior. For instance, Temple et al. (2003) studied neural changes with reading improvement in dyslexic children. They started with well-established brain differences between dyslexics and non-dyslexics in the temporo-parietal regions of the brain during reading. They administered an on-the-market training program to dyslexic children, and measured their brain responses before and after. The children's brain activity in the temporo-parietal regions increased after training, as did their reading abilities. The study's focus was on the concurrence of normalized brain activity and improved reading performance, with less emphasis on the features of the training that led to each of these. The contextual manipulation primarily served to strengthen causal claims about the relation between brain and behavior.

Culture B focuses on the contextual features themselves. Culture B's strength resides in connecting contextual factors to behavior on the one hand and to brain responses on the other. Researchers predict how a given contextual factor will lead to specific behaviors and behavioral

change. An instance comes from the prediction that drawing letters leads to better visual recognition than naming letters (James, 2010). At the same time, a researcher might ask, how does this contextual difference influence the involvement of specific brain regions? Studying the neural and behavioral responses to contextual factors then helps the researchers specifically describe the contextual effects, which can inform the next contextual manipulation. For example, one might consider using hands-on activities to drive superior visual recognition in other domains, such as learning to recognize birds, which in turn, may raise questions about the best types of hands-on activities.

One way to appreciate these inquiry differences is to consider the nature of the likely applied outcomes. Culture B is likely to yield solutions that will be effective manipulations to contextual variables such as instruction. Contextual manipulations provide the strongest evidence about the effects of context on behavior. Culture A may also focus on behavioral treatments, but it is not unreasonable to anticipate biological solutions. Biological manipulations provide the strongest evidence about the biology of the brain and its relation to behavior. For example, clinical conditions, such as dyslexia, often show a strong heritable component (Gabrieli, 2009). Culture A researchers may look towards biologists for help in designing gene therapies that prevent dyslexia before a child reaches the context of reading instruction.

THE DESIRED EDUCATIONAL OUTCOMES

Culture A: Address Hard Practical Problems

The theoretical contributions of Culture A are often in the domain of neuroscience, for example, by modeling the brain networks involved in reading. The translation between this kind

of brain-based model and operational educational theories is difficult. The educational outcomes of Culture A research are less likely to be in educational theory, and more likely to address difficult practical problems that can be of clinical magnitude. For example, researchers might develop brain-based measures of dyslexia, and help determine which sub-skills are causing difficulty so remediation can be precisely targeted. The justification for this program of work, beyond the basic science, is the desired outcome of remediating the difficulties (e.g., Simos et al., 2002; Shaywitz et al., 2004).

The program of work is largely done by behavioral neuroscientists, but there are ways that educators can contribute to their efforts. One contribution involves identifying important educational domains that are challenging for children, and specifying the kinds of difficulties children experience. Educators can develop behavioral assessments that can sort children with respect to the difficulty. These assessments are highly important to the individual differences approach. Not only do they help pinpoint the difficulties that some children may have, but they also help control for other factors. For example, in many neuroscience studies, it is common practice to match the participants on IQ score to ensure that any resulting individual differences are not due to general considerations of brain functioning, but rather they are due to selective difficulties. A battery of good measures can ensure that the neuroscientist is studying dyslexia *per se*, and not a much more diffuse problem that affects many behaviors.

A second place that educators can contribute is by providing instruction. Behavioral neuroscientists are in the business of diagnosis and explanation, and educators can help with models of treatment. However, it is important to note that clinical problems often demand forms of instruction that may not be ideal for regular classrooms, though warranted for clinical

treatment (e.g., hundreds of hours of difficult repetitions accompanied by simple rewards).

Educators who help design instruction for neuroscience may need to set aside some of what they

know about making well-rounded students. Producing solutions to hard clinical problems is

unlikely to inform classroom practices in the near term, but it may affect who makes it to the

classroom.

<div style="text-align:center">Culture B: Address Hard Theoretical Problems</div>

Culture B takes the viewpoint of educational researchers. While most educational

research also targets specific practical problems, such as developing the most effective curricula

for teaching place value, much of the work is also aimed at broad theoretical debates about

learning. This may seem surprising given the applied nature of education. However, orienting

theories are important for decision-making. Educators often encounter situations that do not

correspond to any single piece of research, and they need to make decisions to handle the

hundreds of possible *in situ* factors. In education, there are few things so practical as a good

theory.

People do not need to be theory experts to inform their practice. For example, the

Russian psychologist Lev Vygotsky is an important source of educational guidance. A typical

educator does not need to know how Plato's theories influenced Hegel, who in turn influenced

Marx, from whom Vygotsky derived much of his framework. For an educator, it may be

sufficient to understand Vygotsky's theory that social mediation drives development when it

occurs within the "zone of proximal development" (Vygotsky, 1978). If nothing else, this helps

the educator understand that focusing exclusively on cognitive aspects of learning is too narrow.

One of the great potentials of neuroscience for education is that it can provide new types

of orienting theories that are useful to educators. In a Culture B approach, one might start with difficult standing theoretical problems that have defied prior attempts to reach a resolution. There are a number of candidates including debates over *being told* versus *discovery* (Tobias & Duffy, 2009), *decomposing tasks* versus *authentic practice* (Barron et al., 1998), and providing *concrete experiences* versus *abstract principles* (McNeil & Uttal, 2009). Brain-based theories may help to resolve some of these theoretical knots, and in the process, inspire new models of instruction. We provide an extended example from our own on-going work for what this might look like.

An Extended Example: The Bundling Hypothesis

The theoretical problem we are working on is the relation between perceptual-motor activity and abstract understanding, particularly in early mathematics learning. This has been a difficult theoretical problem, and there is a good deal of confusion among educators for how to think about using concrete activities including hands-on activities (Blair & Schwartz, in press). Cognitive science, which produces formal models of cognition, has also found it challenging to account for the relation of perceptual-motor activity and abstraction, with some authors proposing that all cognition is embodied (Lakoff & Nunez, 2000), and other authors proposing that all cognitive representations are amodal and independent of perceptual processing (Newell, 1990). Developmental psychology has also seen unresolved debates. For example, Piaget (1941/1952) proposed a concrete to abstract shift in thinking through a process of reflective abstraction. In contrast, Spelke (2000) proposes that core representations of abstract concepts are innate. Given the long-standing difficulties of resolving the relation of perceptual-motor activity and abstract understanding, neuroscience-inspired theories and data may provide a fresh

alternative.
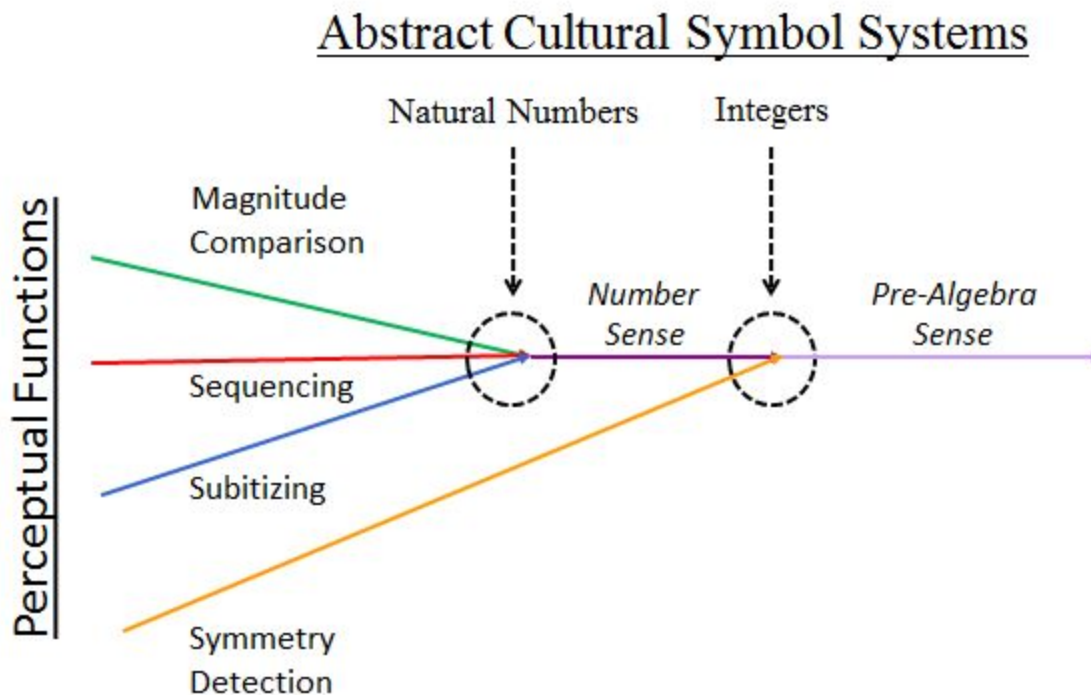
Figure 3. The Bundling Hypothesis. Cultural symbol systems help bind innate perceptual-motor foundations to create increasingly structured mathematical understanding.

Our specific example of a neuro-inspired theory is called the *bundling hypothesis*. One proposition of the theory is that people have discrete perceptual competencies, and they get bundled together to provide new mathematical structure and meaning. A second proposition is that activity with abstract cultural symbol systems coordinates the bundling of these otherwise independent perceptual systems. Figure 3 provides a schematic of this process for the natural numbers and then the integers, which include zero and the negative numbers.

For the natural numbers, Robbie Case and colleagues (Case et al., 1997) hypothesized that number sense depends on integrating different quantitative competencies that appear separately in infants and animals as basic perceptual-motor schemes. For example, infants can

discriminate the magnitudes of events (sound, size); they can order their own physical movements; and, they can distinguish several objects without enumerating (i.e., subitizing). According to the bundling hypothesis, these discrete perceptual-motor uses of quantitative information are integrated through the symbolic structures of mathematics. For example, the digit 5 can refer to the magnitude of a sound (5 decibels); it can refer to the order of a sound (fifth); and, it can refer to the amount of sounds (5 taps). In instructional studies, Case and colleagues found that instruction that integrates these quantitative meanings is more effective than instruction that strengthens each separately (Griffin, Case, & Siegler, 1995).

Neuroscience methods are difficult to use with very young children (they move a lot), so we examined the bundling hypothesis in the context of learning integers, which are often not taught until age 10 and beyond. Additionally, the integers are more abstract than the natural numbers, and therefore, they provide a better test case for the bundling hypothesis. Integers are more abstract in the sense that one does not perceive negative objects. Moreover, zero may be the prototypical example of an abstraction – structure without perceptual substance. Integers also introduce new structure to number systems including the additive inverse ($X + -X = 0$) and the additive identity ($X + 0 = X$). To make sense of these new structures, our hypothesis is that people recruit perceptual sub-systems that handle symmetry (e.g., Varma & Schwartz, in review).
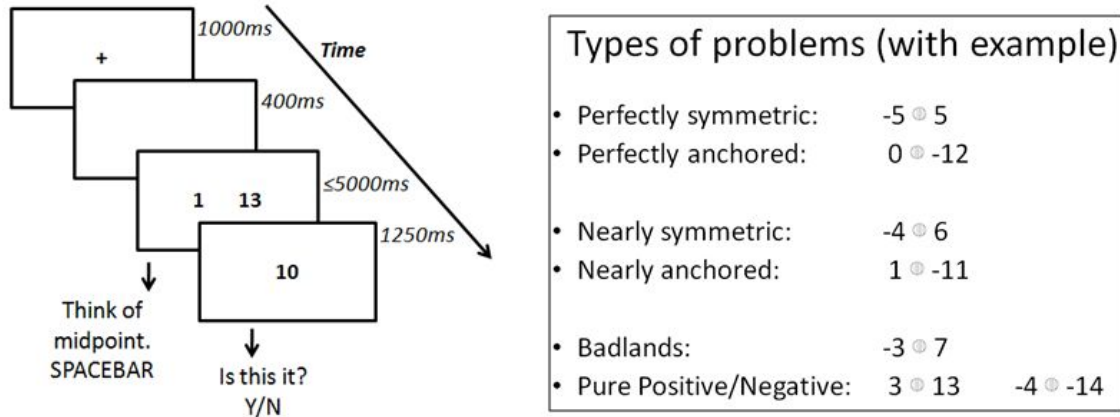
Figure 4. Behavioral Task for Detecting if People Recruit Symmetry for a Purely Symbolic Task.

Evidence on the Bundling Hypothesis

To make headway on the hypothesis, we developed a behavioral paradigm that could eventually be used in an fMRI paradigm (which usually depends on many repetitive trials). We asked adults to find the bisection of two symbolic digits (Tsang & Schwartz, 2009). For instance, "what is the mid-point of -4 and 6?" If people have recruited symmetry to make sense of the integers, then bisection problems that are closer to symmetry about zero should be solved more quickly. The left side of Figure 4 shows the basic task, and the right side shows examples of the types of problems people received. There were perfectly symmetric problems and perfectly anchored problems. Badland problems were as far away from either as possible, and nearly symmetric and nearly anchored problems were somewhere in between.
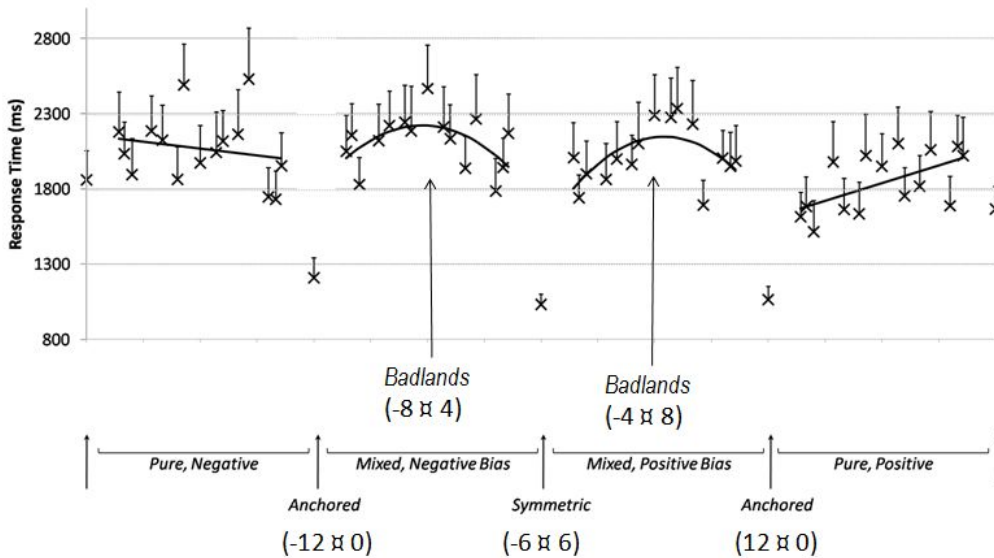
Figure 5. People Bisect Two Digits Faster when the Digits Approximate the Additive Inverse (symmetric) or are Anchored on Zero. Adapted from Tsang & Schwartz (2009).

Figure 5 shows how long it took people to answer the bisection problems. When problems were perfectly symmetric or anchored, people were very fast, presumably because these were well-memorized number facts. Of more interest are the "tuning" curves. People became progressively faster as the digits neared quantitative symmetry about zero. Although the task was purely symbolic and the digits always appeared in the same display locations, people seemed to be taking advantage of the implied quantitative symmetry.

People also responded faster as problems became more anchored (one of the digits was a neighbor of zero). Was the same underlying process responsible for the improved performance for the symmetric and anchored sides of the curve, or was the symmetry performance due to symmetry specific processes? This is where neural evidence can be useful. It may show differences in underlying process despite behavioral similarities.
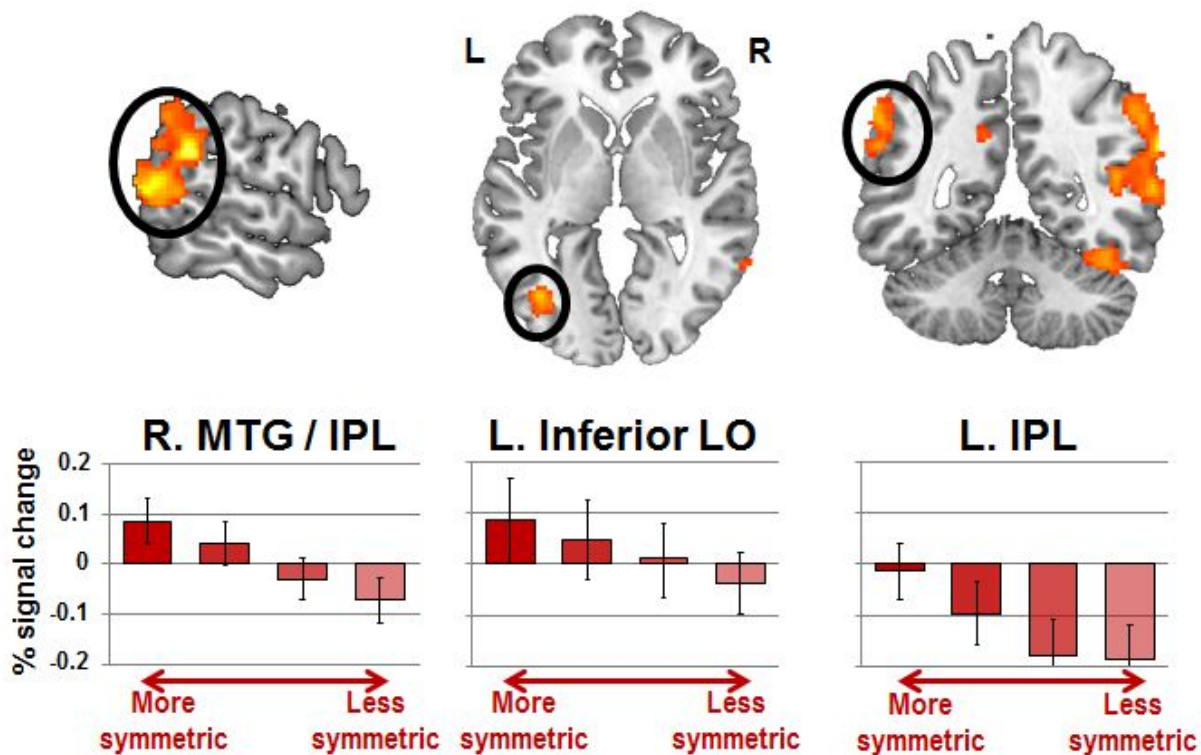
Figure 6. Areas of the Brain that Increased Activation as Bisection Problems Increased in Symmetry about Zero. The top panel shows the location in the brain of three areas that increased activation as the implied symmetry of the digit pairs increased (i.e., the degree to which the two digits approximated the additive inverse). The bottom panel plots the activation changes as the digit pairs became more and less symmetric. All areas of the brain are constantly active, and percent signal change refers to the change in activity over a baseline level.

We conducted the same study in an fMRI paradigm (Tsang et al, 2010). Figure 6 shows three regions that increased activity as problems became more symmetric. These three regions did not show increased activity as problems became more anchored, despite similar reductions in response time. The results suggest that these regions are capitalizing on the implied symmetry to help complete the task. Supporting this interpretation, the left Inferior LO (lateral occipital) cortex is implicated in the perception of visually symmetric stimuli (Sasaki, Vanduffel, Knutsen, Tyler, & Tootell, 2005; Tyler et al., 2005) and regions close to the right MTG (medial temporal

gyrus) and nearby superior temporal regions are implicated in visual bisection tasks (Wilkinson & Halligan, 2003; de Schotten et al., 2005).
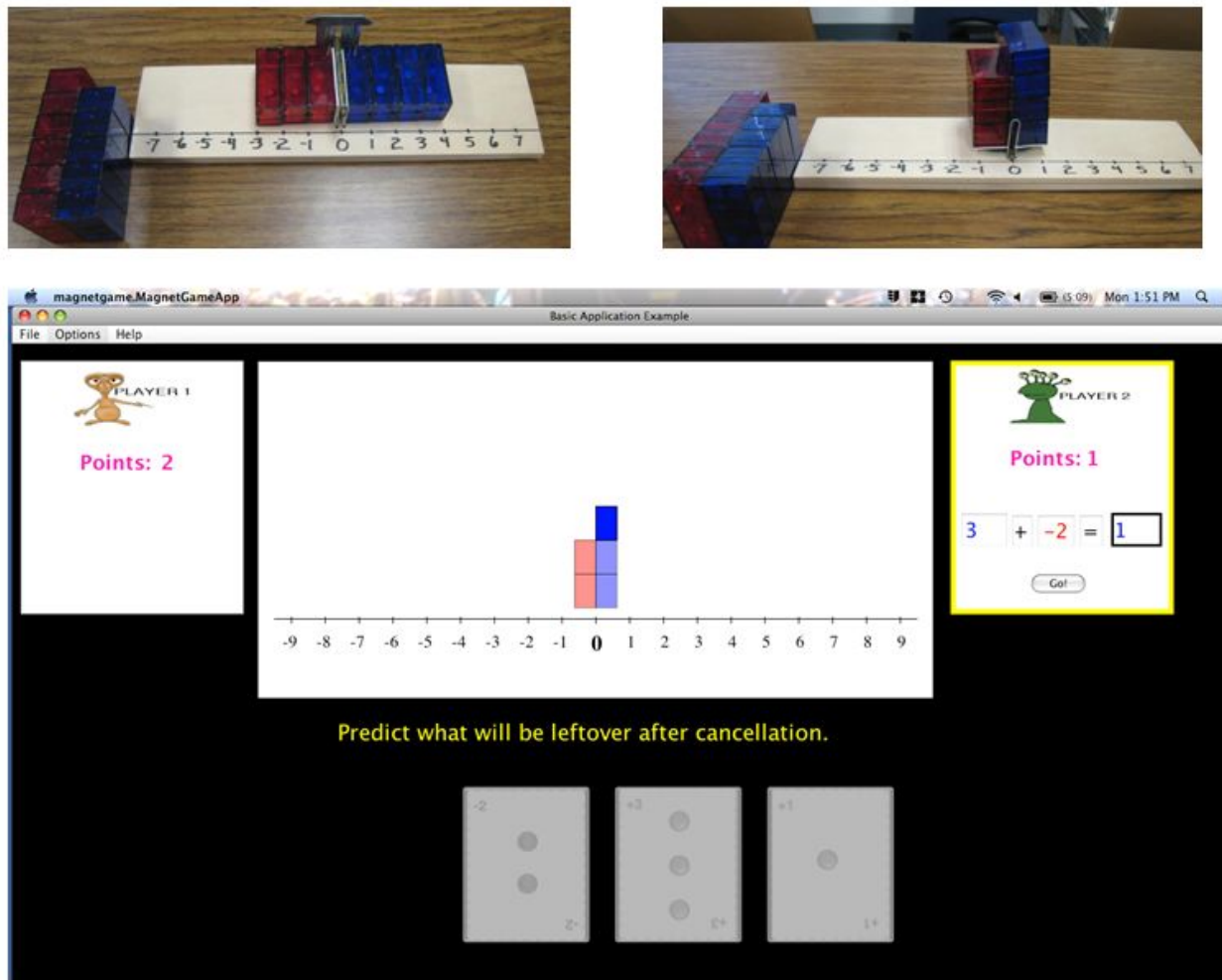
Figure 7. New Models of Instruction to Help Students Learn the Integers with an Emphasis on Symmetry.

Implications for Future Research and Practice

The fMRI data provide initial support for the bundling hypothesis. In the case of the integers, the brain appears to recruit relevant perceptual abilities to help make the mathematical

abstractions meaningful and support mathematical operations. The results suggest that introducing symmetry into early integer instruction may be useful.

Therefore, we have been developing hands-on activities (Figure 7, top panel) and computer games (bottom panel) that emphasize symmetric relations about zero. These materials are different from the common approaches to teaching negative numbers, which often emphasize walking back and forth along a number line (the ordering aspects of integers but not their symmetric properties). Our behavioral hypothesis is that enabling students to recruit and integrate symmetry into their representation of number will produce a stronger foundation in the integers, which will support future learning in topics like algebra. Our brain hypothesis is that children who complete these activities will also show more recruitment of the brain regions involved in visual symmetry for problems relevant to the additive inverse. Finally, the instructional materials enable us to examine broader theoretical claims, such as the role of cultural symbols in recruiting and bundling perceptual systems. For example, a control condition could complete the same symmetry-based activities without the integer digits being present. (They would have separate more traditional lessons on the integers.) The bundling hypothesis predicts that they will not incorporate symmetry into their representation of the integers as a result of this instruction.

The purpose of this extended example is to give an idea of how the Culture B approach can make headway. By taking on hard theoretical problems relevant to instruction, it is possible to generate new types of theories that can clarify long-standing debates. Additionally, the instantiation of the theory in specific topics, such as learning integers, begins to generate new testable ideas about instruction and its effects on both behavior and brain organization. Time

will tell whether this instance of Culture B achieves its aspirations. In the meantime, it provides a workable complement to Culture A for bridging education and neuroscience.

INTERDISCIPLINARY COLLABORATION

For both Cultures A and B, collaboration is central. Currently, there are very few educational neuroscientists, so the work depends on interdisciplinary collaborations. We begin by describing what we take as the standard approach to these collaborations. We then suggest an alternative approach and provide an example. These types of collaborations may best be understood through the metaphor of building a relationship. While some of the metaphor is tongue in cheek, the quotes that we include are paraphrases of statements we have heard over the years, and typically more than once.

The Typical Stages of Collaboration

Stage 0: Blind Dating. For example, a researcher may want to submit a grant that has an educational neuroscience component. Because the person cannot cover all the requisite disciplines, he or she starts to send emails to possible collaborators. After a few exchanges, there is a first meeting.

Stage 1: Borrowing. Much like people may borrow a cup of sugar to pursue a relationship, researchers may ask if they can borrow some expertise and connections. For example, the neuroscientist might ask, "Can you get me subjects from the schools?" or "Do you have a validated test of math dysfunction?" The educational researcher might ask, "Can you scan my students writing a poem?" The questions are naturally naïve because both parties are making assumptions about what the other person knows and does.

Stage 2: Giving. When deepening a relationship, people may ask a partner to take on a small responsibility, for example, taking care of a plant. Similarly, researchers further test the waters by granting/requesting small responsibilities. For the neuroscientist, the request might be, "Would you take care of my need to teach kids nonsense syllables?" For the educator, it might be, "I have this kid is who having a really hard time. Could you scan him to see what it is?" Bruce McCandliss, an educational neuroscientist, has referred to the collaborative activity in the Borrowing and Giving stages as, "throwing a cow over the fence" (personal communication). There is a belief that it is possible to partition the tasks so fully that the collaboration involves throwing things back and forth rather than each party trying to understand both the biological and contextual questions.

Stage 3: Moving in. As relationships become more serious, one person may move into the home of another. An educational researcher may work on the neuroscientist's problems, or vice versa. It can be difficult to retain one's identity in the other person's house. It is possible, but it is hard to sustain the active intellectual identity, questions, and sensibilities that led one to want to collaborate in the first place.

<center>Incremental Progress versus Novel Phenomena</center>

Several aspects of the preceding model work well when there are mature relations between fields. For example, when building a space telescope, it is possible to partition the task by different types of disciplinary expertise and hand-off results between one another. The specific contributions of each discipline can be well-coordinated within an overarching plan and the common explanatory paradigm of physics and the language of mathematics. Collaborations within Culture A often aspire to this level of maturation. For example, the neuroscientists will

take care of the brain-based hypotheses, and educators will take care of the behavioral assessments and instruction. The model is one of incremental progress, where educators can help neuroscientists take the next step in addressing their well-formed brain-based questions. The assumption of having someone move into your research house is typically that they will help you make progress on what you are doing, not transform what you are doing.

To help develop Culture B, we suggest a different model of collaboration. Giyoo Hatano (Hatano & Inagaki, 1986) made a distinction between routine experts and adaptive experts. Routine experts are highly efficient at recurrent tasks in their domain of expertise. If a collaboration forms that lets people stay within their routine expertise, they will have little reason to stretch to understand another intellectual agenda deeply. This is not an ideal collaboration, because it diminishes the odds of cashing out the interdisciplinary promise for theory and evidence that are important to both neuroscientists and educators.

In contrast to a routine expert, Hatano described adaptive experts as people who take on new types of challenges and have the knowledge and dispositions to do so. One of the pre-requisites for developing adaptive expertise is being in situations where it is possible to explore rather than just perform. To encourage an adaptive expert approach to developing Culture B, we suggest building a new house for the relationship rather than moving into one person's or another's. One way to foster this type of collaboration is to begin with a newly discovered phenomenon that is not directly within any of the collaborators' immediate expertise.

Our example comes from work in a science of learning center funded by the U.S. National Science Foundation. The center is called LIFE, which stands for Learning in Informal and Formal Environments (www.life.org). The center was explicitly funded to do

transformative, interdisciplinary work on the topic of learning. In the early days of the center, the research scientists were already pursuing important questions of their own. They naturally wanted people to move into their homes. In some cases, this worked, but a group of faculty decided to go after a new phenomenon to see if people could "let go" of their routine expertise and join together to work on a novel (to them) problem.

It took over a year of weekly meetings to gain traction. The group ultimately decided to see if they could generate a new behavioral phenomenon that sits between the stepping stones of neuroscience and education. They also decided to start with a theoretical bottleneck in the learning sciences. A very large literature on social facilitation has demonstrated that the mere presence of others nearby improves performance for simple tasks but interferes with complex learning (Bond & Titus, 1983). In contrast, a substantial literature on group interaction shows that social exchange often improves complex learning compared to working alone (e.g., Slavin, 1996). To reconcile these two bodies of work, the experiments examined social facilitation in an interactive context. In the original social facilitation research of decades past, it was not possible to exert sufficient control when people interacted, so it was impossible to compare interacting with a person versus interacting with a non-person. In the key study by the LIFE group, participants had identical interactions with a graphical character in virtual reality. The manipulation was whether they thought the character represented a live person or a computer (Okita, Bailenson, & Schwartz, 2007). People who thought they were interacting with a person showed superior learning of a complex science topic, and the learning was correlated with the greater levels of arousal in the social condition. As it turned out, interaction was key to the effects – just listening to a person was little better than interacting with a computer.

The advantage of finding a phenomenon at the middle of the stepping stones is that it could grow in both directions. The neuroscientists in the group used the "social belief" effect to test a basic question about memory (Chen, Shohamy, Ross, Reeves, & Wagner, 2008). They took the social belief manipulation into the scanner. They had to change the content so it was possible to get the many trials necessary to detect memory effects, but they retained the manipulation where participants either thought they were interacting with a person or a computer. The study helped clarify the separable roles of the basal ganglia and the hippocampus for different types of memory encoding. At the same time, the results indicated that the social condition led to increased amygdala activation, which is associated with reward and may drive associations among declarative facts. Thus, the behavioral phenomena permitted a test of a question dear to the neuroscientists, while at the same time the fMRI work began to develop the brain-based explanation for the behavioral effect.
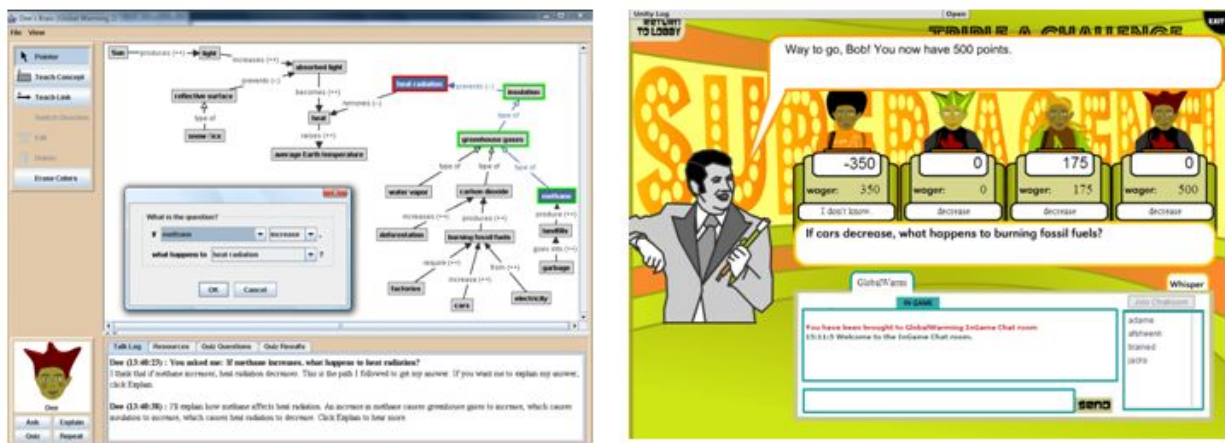
Figure 8. Teachable Agents Software Used to Test whether the "Mere Belief" of Teaching an Agent Led to Better Learning. The left panel shows the teaching interface, where children can add nodes and links, and ask their agent to answer questions, and see how the agent reached its answer. The right panel shows the agents answering questions in an on-line game show, where the children wager on whether their agent will give the right answer.

In the meantime, another set of the researchers looked to the classroom. They used a technology called a Teachable Agent (Biswas, Leelawong, Schwartz, Vye, & TAG-V, 2005; Chin et al., in press). The left panel of Figure 8 shows the teaching interface. Students teach a graphical agent by making a causal map of nodes and links. The agent uses simple artificial intelligence techniques to reason about what it has been taught. The right panel shows the agent answering questions in an on-line game show that students play. The host asks the agents questions, and the students wager on whether the agents will give the correct answers.

In one series of classroom studies (Chase, Chin, Oppezzo, & Schwartz, 2009), the teachers told the children in a Teach condition that they were teaching an agent about biology – the graphical character on the screen represented their pupil. In a Self condition, the children used the exact same software. The difference was that the teachers told the students that they were using a new type of intelligent software to learn, and there was no metaphor of teaching an agent. The graphical character simply represented the student him or herself. The Teach students learned more as measured on a posttest. The effect was especially pronounced for the lower-achieving students. In a subsequent protocol study, it turned out that the Teachable Agent provided an ego-protective buffer. When the agent gave an incorrect answer, the students took responsibility rather than ignoring the failure. This finding has led the group to consider that the effect of "social belief" may be especially tied to negative feedback, which is leading to a new round of fMRI work as well as extensions to new uses of learning technologies that manipulate the implied socialness of the experience, for example, by literally taking the visual point of view of another (Lindgren, in review).

In this example of our proposed Culture B collaboration, it is useful to note that the researchers were not working together to create a single explanation or mechanism. Instead, they were taking a novel phenomenon that they could address at biological, behavioral, or educational levels of explanation. The scientists were trying to produce a corridor of explanation. Each level of analysis tried to understand the phenomenon at that level of explanation. It is unreasonable to expect a single explanation of all the levels, from brain to classroom. However, because of the similarity of the contextual manipulation, it is possible to start making informed links between the levels. Ideally, the different levels of explanation will fully link up, much like the different levels of biological explanation have managed to explain themselves on their own terms, while chaining connections across different scales (e.g., ecosystems to organisms to cells). Whether educational neuroscience will ever generate a mature corridor of explanation is a good question. In the meantime, the approach was extremely generative and produced a number of useful studies in their own right.

TRANSLATING THE RESEARCH

As neuroscience gains traction on educational issues, how will its findings be translated to practitioners? The rise of "neuro-myths" tells us something important. People like to think with brain-based explanations, and many teachers in the U.S. are enamored of them. One can imagine a number of possibilities for why this is so. For example, neuroscience has the credibility of a *real* science; Americans are materialists and therefore prefer material explanations; teachers can use brain explanations to abnegate responsibility ("something is wrong with that kid's wiring"). A different guess is that people are very good at creating and reasoning with spatial mental models (e.g., Kieras & Boviar, 1984). If one returns to Figure 2,

which shows the white matter fibers, it is not hard to generate explanations for how differences

in physical structure would cause differences in behavior. Compared to reasoning about abstract

constructs such as metacognition, schemas, or the compilation of declarative facts into

procedural skills, thinking about physical connections seems quite easy. Carol Dweck, for

example, has been successful at teaching children that their brains are plastic, which has led to

more mastery behaviors on the children's part (http://www.brainology.us; Blackwell,

Trzesniewski, & Dweck, 2007). It is not as though children do not regularly hear they can learn.

However, the spatial model of the brain makes it easier for them to think about learning and

change. Of course, ease does not mean accuracy, which is why neuro-myths arise. Therefore, it

is important for us to translate results well.

One approach to translation can be described with an analogy: Neuroscience findings are

to educators, as drugs are to pharmacists. In this model, educational neuroscientists come up

with prescriptions, and it is the job of the educator to dispense them with care.   The model

works well for many types of innovations, and it is primarily about implementation and going to

scale, rather than translating findings so people can think about them for themselves. This

implementation approach concerns us, however, because it is likely to be quite alienating to

educational researchers, who are generally the people who teach the educators. The risk of

alienation is already presaged by a common reaction to neuroscience research among education

faculty, "What does it matter where it lights up in the brain, if I can already see the behavior?"

A second analogy captures an alternative translational approach: Neuroscience findings

are to educators, as drugs are to doctors. In this model, educators have the skill to interpret

findings, not just dispense prescriptions. They need some understanding of the science and not

just packaged results. Knowing a few facts can help people imagine and evaluate the possibilities, and they may even be an incentive to learn more.

What type of translational curriculum could support educators to adopt an interpretation-heavy use of neuroscience findings? Current approaches appear to favor the biology of the brain with a heavy dose of anatomy and neuro-transmitters. We respectfully suggest it may be worthwhile to weight the content of lessons for educators more towards the methods of neuroscience. Nearly all educational science standards emphasize tools and methods of inquiry, and so it should be with educational neuroscience. With a modest grasp, people can begin to think about what is and is not possible. For example, many of our educator colleagues find surprising the large number of stimuli repetitions necessary in fMRI (to separate the signal from noise). Moreover, educators may not know that people are restricted to little finger movements to indicate a response. For people interested in the effects of context, these details resonate because they help create a contextual model for what types of research can and cannot be done in the scanner.

Of course, some methods are esoteric and less important for translation, even if they are essential to the science itself. For example, it probably is unnecessary to teach voxel-wise alpha correction. But, knowing about the subtraction methodology of fMRI is essential for interpreting the brain images found in the neuroscience reports. Picking which methodological facts to present is no different from developing any curriculum, and it takes some experience and thoughtfulness. Translation work should provide people with an entry to how the science does its work and not solely its findings or prescriptions.

CONCLUSION

In summary, we have tried to clarify two possible cultures of educational neuroscience. Their differences are largely practical and cultural rather than theoretical. We have drawn the distinctions in strong relief, and of course, there is nuance. Even so, well-defined contrasting cases help people discern features they might have otherwise overlooked, much as tasting wines side-by-side can highlight flavors missed when tasting a single wine alone.

At the same time that Cultures A and B differ, they both show signs of a similar and profound philosophical shift regarding mind-body dualism. The basic philosophies by which we organize the world are often beset with irreconcilable dualisms. In ancient times, the dichotomy was between the perfect heavens and the imperfect world. Since Descartes, a dominant dualism has separated mind and body. For example, how could a sense of purpose arise from chemicals? The famous philosopher of science, Thomas Kuhn, pointed out that a characteristic of scientific revolutions is not that they always resolve dualisms. But, rather those dualisms become irrelevant as interest and explanation move into a new historical paradigm. For both Culture A and B, the dualism of mind and body seems non-problematic – whatever categorical differences separate mind and brain, these do not seem to impede the practical or scientific progress of educational neuroscience, and they are not a major focus of theorizing. Our hope is that a new dualism does not take its place, namely a dichotomy between the highly contextual and sociological phenomena of education and the biological and often genetic phenomena of neuroscience.

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REFERENCES

Anderson, D.R., Bryant, J., Murray, J.P., Rich, M., Rivkin, M., & Zillmann, D. (2006). Brain
imaging – An introduction to a new approach to studying media processes and effects.
Media Psychology, 8, 1-6.

Ansari, D., & Coch, D. (2006). Bridges over troubled waters: Education and cognitive
neuroscience. Trends in Cognitive Sciences, 10, 146-151.

Ansari, D., Garcia, N., Lucas, E., Hamon, K., & Dhital, B. (2005). Neural correlates of symbolic
number processing in children and adults. Neuroreport 16, 1769–1773.

Baron-Cohen, S., & Belmonte, M. K. (2005). AUTISM: A window onto the development of the
social and the analytic brain. Annual Review of Neuroscience, 28, 109-126.

Barron, B. J., Schwartz, D. L., Vye, N. J., Moore, A., Petrosino, A., Zech, L., Bransford, J. D., &
CTGV. (1998). Doing with understanding: Lessons from research on problem- and
project-based learning. Journal of the Learning Sciences, 7, 271-312.

Biswas, G., Leelawong, K., Schwartz, D. L., Vye, N., & TAG-V. (2005). Learning by teaching:
A new agent paradigm for educational software. Applied Artificial Intelligence, 19,
363-392.

Blair, K. P. and Schwartz, D. L. (in press). The value of concrete learning materials in
adolescence. To appear in Reyna, V., Chapman, S., Dougherty, M. & Confrey, J. (Eds.)
The Adolescent Brain: Learning, Reasoning, and Decision Making.

Blackwell, L. S., Trzesniewski, K. H., & Dweck, C. S. (2007). Implicit theories of intelligence
predict achievement across an adolescent transition: A longitudinal study and an

intervention. <u>Child Development, 78</u>(1), 246-263.

Bond, Jr. C. F., & Titus, L. J. (1983). Social facilitation: A meta-analysis of 241 studies.

<u>Psychological Bulletin, 94</u>, 265-292.

Bruer, J. T. (1997). Education and the brain: A bridge too far. <u>Educational Researcher, 26</u>, 4-16.

Butterworth, B. (2005). Developmental dyscalculia. In J. I. D. Campbell (Ed.), <u>Handbook of</u>

<u>Mathematical Psychology</u> (pp. 455–67). Hove: Psychology Press.

Camerer, C., Loewenstein, G., & Prelec, D. (2005). Neuroeconomics: How neuroscience can

inform economics. <u>Journal of Economic Literature, 43</u>, 9-64.

Case, R., Okamoto, Y., Griffin, S., McKeough, A., Bleiker, C., Henderson, B., Stephenson,

K.M., Siegler, R.S., & Keating, D.P. (1997). The role of central conceptual structures in the

development of children's thought. <u>Monographs of the Society for Research in Child</u>

<u>Development, 61</u>, 1–295.

Castellanos F. X., Sonuga-Barke E. J. S., Milham M. P., & Tannock R. (2006). Characterizing

cognition in ADHD: beyond executive dysfunction. <u>Trends Cognitive Science, 10</u>, 117–123.

Chase, C., Chin, D. B., Oppezzo, M., & Schwartz, D. L. (2009). Teachable agents and the

protégé effect: Increasing the effort towards learning. <u>Journal of Science Education and</u>

<u>Technology, 18</u>, 334-352.

Chen, J., Shohamy, D., Ross, V., Reeves, B., & Wagner, A. D. (2008). The impact of social

belief on the neurophysiology of learning and memory. <u>Society for Neuroscience Abstracts</u>.

Chin, D. B., Dohamen, I., Oppezzo, M., Cheng, B., Chase, C., & Schwartz, D. L. (in press).

Preparation for future learning with Teachable Agents. <u>Educational Technology Research</u>

<u>and Design.</u>

D'Amato, R. C., Fletcher-Janzen, E., & Reynolds, C. R. (2005). Handbook of School

Neuropsychology. Hoboken, NJ: John Wiley & Sons.

Delazer, M., Ischebeck, A., Domahs, F., Zamarian, L., Koppelstaetter, F., Siednetopf, C. M.,

Kaufmann, L., Benke, T., & Felber, S. (2005). Learning by strategies and learning by drill –

evidence from an fMRI study. NeuroImage, 25, 838-849.

de Schotten, M. T., Urbanski, M., Duffau, H., Volle, E., Levy, R., Dubois, B., et al. (2005).

Direct evidence for a parietal-frontal pathway subserving spatial awareness in humans.

Science, 309(5744), 2226.

Dorsey, R., Vitticore, P., de Roulet, J., Thompson, J. P., Carrasco, M., Johnson, S. C., Holloway,

R. G., & Moses III, H. (2006). Financial Anatomy of Neuroscience Research. Annuals of

Neurology, 60, 652-659.

Gabrieli, J. D. E. (2009). Dyslexia: A New Synergy Between Education and Cognitive

Neuroscience. Science, 325 (5938), 280-283.

Gibson, E. (1969). Principles of perceptual learning and development. New York:

Appleton-Centrury-Crofts.

Goswami, U. (2006). Neuroscience and education: From research to practice. Nature Reviews

Neuroscience, 7, 406-413.

Griffin, S., Case, R., & Siegler, R. (1994). Rightstart: Providing the central conceptual

prerequisites for first formal learning of arithmetic to students at-risk for school failure. In

K. McGilly (Ed.), Classroom lessons: Integrating cognitive theory and classroom practice

(pp. 24–49). Cambridge, MA: Bradford Books MIT Press.

Hatano, G., & Inagaki, K. (1986). Two Courses of Expertise. In H. Stevenson, H. Assume, & K. Hakuta (Eds). Child development and education in Japan (pp. 262-272). New York: Freeman.

James, K. H. (2010). Sensori-motor experience leads to changes in visual processing in the developing brain. Developmental Science, 13, 279–28.

Kieras, D.E. & Boviar (1984). The Role of a Mental Model in learning to operate a device. Cognitive Science, 8, 255-273.

Kuhl, P.K., Conboy, B.T., Padden, D., Rivera-Gaxiola, M., & Nelson, T. (2008). Phonetic learning as a pathway to language: new data and native language magnet theory expanded (NLM-e). Philosophical Transactions of the Royal Society B, 363, 979–1000.

Lakoff , G & Núñez. R. (2000). Where Mathematics Comes From: How the Embodied Mind Brings Mathematics into Being. New York: Basic Books.

Lindgren, R. (under review). Embodied expertise: Perspective-based learning in a virtual world simulation.

McDermott, R. (2004). The feeling of rationality: The meaning of neuroscientific advances for political science. Perspectives on Politics, 2, 691-706.

McNeil, N. M., & Uttal, D. H. (2009). Rethinking the Use of Concrete Materials in Learning: Perspectives From Development and Education. Child Development Perspectives, 3(3), 137-139.

Menon, V., Rivera, S. M., White, C. D., Eliez, S., Glover, G. H., & Reiss, A. L. (2000). Functional optimization of arithmetic processing in perfect performers. *Cognitive Brain Research, 9*(3), 343-345.

Molfese, D. L., (2000). Predicting dyslexia at 8 years of age using neonatal brain responses. Brain and Language, 72, 238-245

Newell, A. (1990). Unified theories of cognition. Cambridge, MA: Harvard University Press.

O'Boyle M. W. & Gill, H. S. (1998). On the Relevance of Research Findings in Cognitive Neuroscience to Educational Practice. Educational Psychology Review, 10 (4), 397-409.

Okita S. Y., Bailenson J., & Schwartz D. L. (2007) The mere belief of social interaction improves learning. In D. S. McNamara and J. G. Trafton (Eds.), Proceedings of the 29th Annual Meeting of the Cognitive Science Society (pp. 1355-1360).

Piaget, J. (1941/1952). The Child's Conception of Number. London: Routledge and Kegan Paul.

Rivera, S.M., Reiss, A.L, Eckert, M.A., and Menon, V. (2005). Developmental changes in mental arithmetic: Evidence for increased functional specialization of the left inferior parietal cortex. Cerebral Cortex, 15(5).

Sasaki, Y., Vanduffel, W., Knutsen, T., Tyler, C., & Tootell, R. (2005). Symmetry activates extrastriate visual cortex in human and nonhuman primates. Proceedings of the National Academy of Sciences of the United States of America, 102(8), 3159-3163.

Shaywitz, B. A., Shaywitz, S. E., Blachman, B. A., Pugh, K. R., Fulbright, R. K., Skudlarski, P., Mencl, W. E., Constable, R. T., Holahan, J. M., Marchione, K. E., Fletcher, J. M., Lyon, G. R., & Gore, J. C. (2004). Development of left occipitotemporal systems for skilled reading in children after a phonologically-based intervention. Biological Psychiatry, 55, 926-933.

Simos, P. G., Fletcher, J. M., Bergman, E., Breier, J. I., Foorman, B. R., Castillo, E. M., Davis, R.N., Fitzgerald, M., & Papanicolaou, A.C. (2002). Dyslexia-specific brain activation

profile becomes normal following successful remedial training. <u>Neurology, 58</u>, 1203-1213.

Slavin, R. E. (1996). Research on cooperative learning and achievement: What we know, what we need to know. <u>Contemporary Educational Psychology, 21</u>, 43-69.

Spelke, E.S. (2000). Core knowledge. <u>American Psychologist, 55</u>, 1233–1243.

Tang, Y., Zhang, W., Chen, K., Feng, S., Ji, Y., Shen, J., Reiman, E. M., & Liu, Y. (2006). Arithmetic processing in the brain shaped by cultures. <u>Proceedings of the National Academy of Science, 103</u>, 10775-10780.

Tobias, S., & Duffy, T. M. (Eds.). (2009). <u>Constructivist instruction: success or failure?</u> New York: Routledge.

Temple, E., Deutsch, G.K., Poldrack, R.A., Miller, S.L., Tallal, P., Merzenich, M.M. & Gabrieli, J.D. (2003) Neural deficits in children with dyslexia ameliorated by behavioral remediation: evidence from functional MRI. <u>Proceedings of the National Academy of Sciences, 100,</u> 2860–2865.

Tsang, J.M., Dougherty, R.F., Deutsch, G.K., Wandell, B.A. & Ben-Shachar, M. (2009). Frontoparietal white matter diffusion properties predict mental arithmetic skills in children. <u>Proceedings of the National Academy of Science, 106</u>, 22546-51.

Tsang, J.M., Rosenberg-Lee, M., Blair, K.P., Schwartz, D.L., & Menon, V. (2010, June). Near symmetry in a number bisection task yields faster responses and greater occipital activity. Poster presented at <u>The 16th annual meeting of the Organization for Human Brain Mapping</u>, Barcelona, Spain.

Tsang, J.M., & Schwartz, D.L. (2009). Symmetry in the semantic representation of integers. In N. Taatgen, & H. van Rijn (Eds.), <u>Proceedings of the 31st Annual Conference of the</u>

Cognitive Science Society (pp. 323-328). Austin, TX: Cognitive Science Society.

Tyler, C. W., Baseler, H. A., Kontsevich, L. L., Likova, L. T., Wade, A. R., & Wandell, B. A. (2005). Predominantly extra-retinotopic cortical response to pattern symmetry. NeuroImage, 24(2), 306-314.

Varma, S., McCandliss, B. D., & Schwartz, D. L. (2008). Scientific and pragmatic challenges for bridging education and neuroscience. Educational Researcher, 37(3), 140-152.

Varma, S. & Schwartz, D. L. (in review). The Mental Representation of Integers: A Restructuring of Analog Magnitudes.

Vygotsky, L. (1978). Mind in society: The development of higher psychological processes. (M. Cole, V. John-Steiner, S. Scribner, E. Souberman, Eds.) Cambridge, MA: Harvard University Press.

Wilkinson, D. T., & Halligan, P. W. (2003). Stimulus symmetry affects the bisection of figures but not lines: Evidence from event-related fMRI. NeuroImage, 20(3), 1756-1764.