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Janet M. Dubinsky[1], Gillian Roehrig[2], and Sashank Varma[1]

Bruer advocated connecting neuroscience and education indirectly through the intermediate discipline of psychology. We argue for a parallel route: The neurobiology of learning, and in particular the core concept of *plasticity*, have the potential to directly transform teacher preparation and professional development, and ultimately to affect how students think about their own learning. We present a case study of how the core concepts of neuroscience can be brought to in-service teachers—the BrainU workshops. We then discuss how neuroscience can be meaningfully integrated into pre-service teacher preparation, focusing on institutional and cultural barriers.

Keywords: mixed methods; neuroscience; observational research; professional development; science education; teacher education/development

There have been a number of calls over the past 15 years for exploring how neuroscience findings could guide educational research and practice (Blakemore & Frith, 2005; Immodino-Yang & Damasio, 2007; Pickering & Howard-Jones, 2007; Varma, McCandliss, & Schwartz, 2008). In an early influential article appearing in these pages, Bruer (1997) argued that this was a "bridge too far"—that the disciplinary distance between neuroscience and education was too great, and extrapolating from the neuroscience laboratory to the classroom would do more harm than good. (The National Research Council's [2000] influential How People Learn similarly urged caution in this regard.) Instead, Bruer (1997) proposed routing through the intermediate discipline of psychology. This appeared then, and appears today, to be a sound strategy. Collaborations between neuroscientists and psychologists have produced an expansive literature with myriad interdisciplinary labels: cognitive neuroscience, developmental neuroscience, social neuroscience, affective neuroscience, and so on. Collaborations between psychologists and educational researchers, and the historically close connection between these fields, have resulted in a number of educational interventions grounded in psychological principles, and a large literature with its own collection of labels: educational psychology, cognition and instruction, learning sciences, and so on. What remains, according to Bruer's model, is to combine these two mappings.

This paper proposes a parallel route to educational neuroscience. The neurobiology of learning, and in particular the core concept of *plasticity*, have the potential to *directly* transform teacher preparation and professional development, and ultimately to affect how students think about their own learning. Far from abstract background material, the core concepts of neuroscience represent practical knowledge that has the potential to inform teacher practice in classroom settings, as well as motivate students to learn.

This paper first advances neuroscience learning concepts that directly inform teaching and learning. These ideas derive from Neuroscience Core Concepts recently explicated by neuroscientists (Society for Neuroscience, 2008). They have the potential to transform teacher preparation and professional development and to ultimately affect how students think about their own learning. The article next evaluates this proposal in a case study of how these neuroscience concepts can be brought to in-service teachers. Empirical evidence is presented for the efficacy of *BrainU*, a summer professional development institute we have developed for middle and high school science teachers. This case study reveals the issues that arise when experienced teachers grapple with the neurobiology of learning and try to integrate these concepts into their pedagogical practice. The article next considers the logically prior question of how neuroscience can be meaningfully integrated into pre-service teacher preparation.

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Table 1
How the Neuroscience Core Concepts Inform Teaching and Learning (Society for Neuroscience, 2008)

	Core Concept	General Implications for Teaching and Learning
1	The brain is the body's most complex organ.	The complexity of an organism's nervous system dictates the range of its behaviors. For science teaching, simpler nervous systems from model organisms provide opportunities to study how nervous systems work.
2	Neurons communicate using both electrical and chemical signals.	The plasticity of chemical synaptic transmission provides a cellular basis for learning and memory. Communication between neurons is strengthened or weakened by patterns of use. All perceptions, thoughts, and behaviors result from combinations of signals among neurons.
3	Genetically determined circuits are the foundation of the nervous system.	Wiring of the brain is remarkably similar among individuals within a species. Individual variations at the synaptic level account for our individuality.
4	Life experiences change the nervous system.	Learned experiences grow new synapses and circuits and turn on nervous system genes, facilitating additional learning. Mental challenges are important for brain function. An individual's regular and novel activities, such as exercise, learning, stress, social interactions, and drug use, all affect synaptic strength. The salience of an event, content piece or experience will determine its retention. Learners come to the classroom with different prior knowledge based upon their culturally learned experiences.
5	Intelligence arises as the brain reasons, plans, and solves problems.	The brain is the foundation of the mind. Intelligence in all domains reflects the accumulated history of synaptic activation among the multiple brain pathways involved. In other words, practicing creative or deductive thinking facilitates further use of these strategies.
6	The brain makes it possible to communicate knowledge through language.	Promoting effective communication fosters information exchange and creative thought and enhances these skills through exercising appropriate neural pathways.
7	The human brain endows us with a natural curiosity to understand how the world works.	The brain tries to make sense of all incoming sensory information and recognizes conflicts, creating predictions and expectations that guide behaviors. Harnessing natural curiosity of young learners engages and motivates them in the innate process of exploring their environment.
8	Fundamental discoveries promote healthy living and treatment of disease.	Application of the knowledge acquired from research will empower students to make healthy lifestyle and social choices and prevent diseases.

Central here are the institutional and cultural barriers that arise when neuroscientists and teacher educators coteach courses.

Neuroscience Concepts That Inform Pedagogy

The goal of bringing the neuroscience of learning to in-service teachers provides a new perspective on instruction, one where teachers come to see themselves as *designers of experiences that ultimately change students' brains*. Understanding that synapses change and that neural circuits develop and strengthen with experiences—*all* experiences, including practice and play, and formal and informal learning—is fundamental for anyone assuming a guiding, mentoring, instructive role. Teachers will benefit from having this perspective in their theoretical toolkit, just as they benefit from understanding learning as changes in processing and representational resources (cognitivism), internalization of cultural symbol systems (sociocultural theory), and so on (Diamond & Amso, 2008; Sternberg & Williams, 2009).

Historically, it has been unclear whether the neurobiology underpinning learning was relevant for educational practice. A new framework for bridging this gap was put forth recently by the Society for Neuroscience (Society for Neuroscience, 2008), in their compilation of *The Neuroscience Core Concepts* (see Table 1). These core concepts distill "big ideas" in the field for nonscientific audiences without sacrificing scientific accuracy, a problem that has plagued prior efforts to bridge directly between neuroscience and education (Bruer, 1997). Key among these concepts is *plasticity*—that the synaptic connections among neurons are plastic and change with experiences, so despite abundant common neuroanatomical features, variations at the synaptic level determine individual performance (Concepts 2 to 4). Plasticity embodies the idea that the strength of the synaptic connections between neurons is dynamic, becoming stronger with use or weaker with inactivity, providing a cellular-level signal that reflects the history of activity. Synchronous plasticity in the neural pathways producing specific behaviors results in observable learning. Beyond this, the Core Concepts emphasize that our brains provide the basis for our individual humanity and the complex behaviors that shape our society. Both of these main ideas—plasticity and emergent behaviors from complex systems—have relevance to education.

Teachers understand that students "use" their brain when learning, thinking, and performing various tasks in a school setting. Appreciating that neuroscientists can pinpoint biological mechanisms where physical, functional, and genetic changes occur in the nervous system in response to a "learned" event can transform the concept of "using the brain" to one of "changing the brain." The latter is much more powerful in providing agency to the learner (when she learns it) and importance for guiding the behavior of the teacher. The Core Concepts also emphasize that human capabilities such as intelligence, communication, curiosity, and problem solving all emerge from the complexity arising from uniquely individual histories of synaptic activation superimposed on top of genetically driven basic

Table 2
Neuroscience Learning Concepts Relevant to the Education Community

	Neuroscience Learning Concept	Connection to Neuroscience Core Concepts
A	Learning strengthens a set of electrical and chemical events at the level of individual neurons that, over time, result in functional associations distributed throughout the brain. The act of remembering opens up this synaptic set for further plasticity.	Core Concepts 2 and 4
B	Behaviors, thoughts, and memories result from activation of different sets of associated synapses and neural pathways. Partial activation of a synaptic set subserving a specific memory can result in reconstruction of that memory with reasonable but variable fidelity.	Core Concepts 1–6
C	Synaptic pathways are loosely grouped into sensory, motor, emotive, homeostatic, attentional, and decision-making systems, among others, within the central nervous system.	Core Concepts 3, 5, and 7
D	Experiences during early childhood development in conjunction with genetically determined development shape these pathways. They continue to change throughout life in response to every interaction. Mastery involves changing the brain system used for executing a task from deliberative to automatic through rehearsal, application, and self-evaluation.	Core Concepts 3 and 4
E	Repeated behaviors or salient experiences influence synaptic and circuit development more than single or irrelevant ones. Only experiences with an emotional stamp become committed to memory; decisions require operational emotional circuits.	Core Concepts 2, 3, 4, and 5
F	Because there are so many neurons (>100,000,000,000) and so many more synapses (~1,000,000,000,000,000) in the human brain, the activation patterns producing similar behaviors in different brains can be largely comparable yet decidedly unique and individual.	Core Concepts 1, 2, and 4
G	Physiological status, e.g., nutritional and hormonal state, stress, availability of oxygen at high altitudes, and adequate sleep, will influence one's ability to learn, remember, and make appropriate decisions. Emotional status implies a specific physiological state.	Core Concepts 3 and 4
H	The complexity of the nervous system endows us with powerful reasoning and communication skills and curiosity about ourselves and our environment. Structured learning environments provide opportunities for building these skill sets.	Core Concepts 5–8

circuits and anatomy (DeFelipe, 2010). In other words, students' fates should not be viewed as a choice between nature *or* nurture, but rather as the interaction of nature *and* nurture (Chourbaji et al., 2008). From a neurobiology of learning perspective, teachers can view their practices as designing and providing the experiences that build students' brains so that appropriate behaviors emerge.

If the ultimate goal of our educational system is to train lifelong learners, then teaching students to appreciate and guide their own learning becomes critical (Nolen, 2012). Providing teachers with a neuroscience perspective will equip them to convey these ideas to their students. Central here is the plasticity inherent in Core Concept 4: that experiences change the nervous system. Connections between neurons are strengthened with use or practice and, conversely, can become weaker without use. This plasticity forms the basis of learning and memory at the single cell level and translates directly to observed behaviors (Malenka & Bear, 2004). Students who understand that their brains are plastic are more willing to struggle to learn difficult content. In a study in middle school classrooms, a treatment group of students was provided instruction on brain plasticity and as a result scored better on the NY State Regents math exam than control students who did not receive the brain plasticity instruction. Control students continued to view their learning capacities as "fixed," consistent with emerging perspectives on motivation and implicit theories of intelligence (Blackwell, Trzesniewski, & Dweck, 2007).

The educational implications of the Core Concepts can be more readily appreciated if the ideas are restated as a more detailed set of concepts emphasizing the neurobiology of learning and memory (Table 2). These neurobiological learning concepts derive from more than 40 years of neuroscience research on synaptic plasticity: the ability of connections between neurons to adapt based on both current and prior history of use. In a formal learning environment, these Neuroscience Learning Concepts inform teachers' understanding of their principal charge, changing the brains of their students.

The idea that memories are formed from synchronously active but sparse connections within a neural network provides a basis for explaining both the distributed and associative nature of memories and the imperfections of our memory systems (Loftus, 2005; Schacter, 1999). Synapses become stronger when activated simultaneously by multiple inputs forming the basis for associativity between experiences conveyed by different but converging neural pathways (Malenka & Bear, 2004). Thus, sensory processing can become integrated with the emotional state and motor planning; complex ideas can form as associations and extensions of simpler previously acquired knowledge (Bechara, Damasio, & Damasio, 2000). Remembering an event, fact, or procedure reactivates the set of synapses that previously encoded them, reopening the initial plasticity along with a probability for further reinforcing or weakening of this activation pattern (Mitchell, Dodson, & Schacter, 2005). The latter forms the basis for the variable and unreliable nature of memory and the blessing of forgetting inconsequential daily details (Schacter, 1999). The changing landscape of synaptic activation and their genetic controls become consequences of behavioral choices and acquired experience.

In a formal learning environment, these neuroscience learning concepts inform teachers' understanding of their principal charge, changing the brains of their students. Natural experiences like learning to walk build circuits by strengthening synapses; the same is true of structured classroom experiences, like learning to read (Dehaene et al., 2010; Gervan, Berencsi, & Kovacs, 2011). The neuroscientific community is currently examining how circuits change with the learning of mathematical concepts (Butterworth, Varma, & Laurillard, 2011). Transfer of functions from a cognitively demanding frontal cortex (executive) circuit to a less attention demanding basal ganglia (habit) circuit occurs with practice and development of expertise (Ericsson, 2006; Pennartz et al., 2009; Rivera, Reiss, Eckert, & Menon, 2005). The emotional salience of an event or choice, as conveyed by autonomic nervous system signals, influences the strength of its associated memory or decision (Morrison & Salzman, 2010). Brain regions previously thought to confer unique functions are now understood to subserve multiple, integrated, cognitive abilities (Diamond, 2000; Scott, McGettigan, & Eisner, 2009). In short, learning engages multiple brain areas, builds salience, distributes memories widely and trains circuits throughout the nervous system.

These Neuroscience Learning Concepts directly guide the in-service and pre-service teacher education we argue for next. This is not to deny that the behavioral and social principles of learning that psychologists and educators apply to teacher education and student learning provide complementary and insightful perspectives (Howard-Jones, 2007, 2010). Given that teachers are among the best cognitive enhancers on the planet (as are parents and siblings)—rewiring students' brains on a daily basis to acquire literacy, numeracy, and reasoning skills (Butterworth et al., 2011; Dehaene et al., 2010)—we argue that teachers benefit from additionally understanding the neuroscience of learning and memory.

Neuroscience Learning Concepts and In-Service Professional Development Workshops

We next consider the educational utility of the neuroscience learning concepts by exploring their transformative potential for in-service teacher professional development. The development of our professional development and related research was guided by the question, How does teaching in-service teachers about the neurobiology of learning improve their pedagogy? To answer this question, we developed, implemented, and researched a sequence of summer professional development workshops collectively called *BrainU*. The grant-funded BrainU workshops were designed according to established national professional development guidelines and research recommendations (Borko, 2004; Garet, Porter, Desimone, Birman, & Yoon, 2001; Loucks-Horsley, Hewson, Love, & Stiles, 1998; National Academy of Sciences, 1996; Supovitz & Turner, 2000).[1] In addition to focusing on content, professional development should directly address how children learn if the expectation of changing teaching practices is to be met (e.g., Corcoran, 1995). This is particularly true when the goal is the implementation of student-centered, reform-based curriculum, such as scientific inquiry in secondary science classrooms (Cohen & Hill, 1998; Fennema et al., 1996). Thus, neuroscience is at the heart of the two major goals of BrainU:

1. Neuroscience is relevant content for both middle and high school science teachers, with direct connections to standards.
2. Neuroscience has the unique feature that it provides the neurobiological basis for learning, thus allowing discussions about student learning to occur within a scientific, psychological, and pedagogical context.

Given that neuroscience coursework is rare for even life science teachers, the inquiry lessons and experiments provided during the professional development served as an authentic learning experience for teachers, allowing them to truly experience the role of learner in an inquiry setting.

Designing workshops that convey neuroscience content in 1–2 weeks of instruction is challenging. Neuroscience is a large discipline, and the choice of material can be overwhelming. Even using the outline provided by the Neuroscience Core Concepts, there is too much to cover. Neuroscience instruction at the undergraduate level typically begins with ionic-, molecular-, and biophysical-level explanations for the generation of electrical activity (Purves et al., 2012). This approach not only makes neuroscience appear difficult but it is unnecessary when emphasizing the Core Concept of plasticity (Keil, Lockhart, & Schlegel, 2010; Purves et al., 2012). In designing the BrainU workshops, we chose primarily to emphasize the neuroscience that supported deepening teachers' understanding of learning, memory, and teaching, and secondarily to include concepts that aligned to national and state science standards. Content elaborated on the central plasticity theme—the ever-changing communication that occurs at synapses and underpins learning—with examples from normal behaviors, development, drug use, and disease. We did not want to provide another "brain-based learning" workshop emphasizing classroom management techniques and overly extrapolated neuroscience findings. We avoided direct discussions of whether or how neuroscience informed pedagogy. Rather, we concentrated on the neuroscience content itself and our modeling of best pedagogical practices that allow teachers to employ neurobiological learning concepts, and specifically for life science teachers to teach neuroscience. That is, we focused on designing and delivering inquiry-based experiences illustrating synaptic function, plasticity, and emergent complexity as a basis for teaching and learning. We believe this combination allowed teachers to gain a deeper understanding of why inquiry pedagogy is effective.

Implementation

BrainU workshops consisted of a 160-hour sequence over a 3-year period, with BrainU 101 spanning 2 weeks and BrainU 202 and 303 spanning a combined 2 weeks (Roehrig, Michlin, Schmitt, MacNabb, & Dubinsky, 2012). We first offered BrainU 101 in 2000, and have continued to offer annual

Table 3
Topics Covered in BrainU Workshops

BrainU 101	BrainU 202 and 303
Neuroscience topics	
Brain structure and function	Autonomic nervous system
Neuronal structure and function	Homeostasis
Sensory transduction and perception	Nervous system development
Control of motor programs	Diseases of the nervous system
How a synapse works	Drug effects on the nervous system
Synaptic plasticity	Stress
Learning and memory	
Emotions and mirror neurons	
Invertebrate vs. vertebrate nervous systems	
Pedagogy employed	
Construction of concepts	Inquiry as a cycle
Active discussions	Critical evaluation of acquired data
Guided inquiry	Visualization of data
Open-ended inquiry	Concept mapping
Evaluation of information sources	Reading of primary literature
Model building	Model building

Note. In addition to the neurobiology of learning, specific topics were added for the life science audience to address specific science standards.

BrainU workshops, exploring different implementation models in multiple iterations. Here we focus on the workshops given between 2000 and 2007. The combined sets of workshops covered a range of neuroscience and pedagogy concepts (see Table 3). In total, 107 teachers participated in this series of BrainU 101s. Although these were primarily middle school science teachers, several elementary, English, mathematics, health, dance, physical education, and AVID teachers enrolled. Of these, 68 additionally completed BrainU 202, with 41 teachers additionally completing BrainU 303. Teachers choosing not to participate in BrainU 202 and 303 largely cited personal time conflicts.

Classroom lesson plans incorporated a variety of minds-on, modeling, and inquiry-based activities including guided and open-ended experiments. (More details on these activities can be found in MacNabb et al., 2006a.) Neuroscience was taught using a series of these lessons that built successively complex understandings of brain function starting with an inquiry lesson on brain plasticity. In this lesson, prism goggles were used to demonstrate how the brain adapts to a new situation. Teachers investigated learning to toss beanbags at a target while wearing prism goggles that created a 15–25° shift in vision and collected data to investigate how quickly the brain adapted to this new situation. Teachers were frequently engaged in inquiry lessons designed for teachers to develop neuroscience content but also for subsequent use with their own students. Because neuroscience was novel content for the teachers, this experience of learning through doing provided information about how their students could meaningfully experience learning in this same manner. Daily pedagogy discussions and informal teacher interactions reflected upon the student-centered pedagogies incorporated in each activity.

The *content goal* of BrainU was to teach fundamental principles of neuroscience including the Neuroscience Learning Concepts, to improve both teachers' and consequently students' knowledge of both neuroscience and how this knowledge translates to learning. The *pedagogical goal* was to promote the implementation of student-centered pedagogies and to provide a more authentic learning environment for students. To determine if we met our goals, we assessed teacher content learning, and we engaged independent, external evaluators to observe teachers' classrooms who were trained to a level of 90% interrater reliability on established protocols, as explained below (Roehrig et al., 2012).

Outcomes

The content goal was achieved. Teachers' performance on an objective measure of neuroscience knowledge (11 multiple-choice questions) increased reliably from pretest to posttest after BrainU 101 (Figure 1A). Equally importantly, their subjective rating of their own knowledge of neuroscience increased reliably after each BrainU course and after each academic year (Figure 1B). This increase was not driven by increased competency in one area, but rather was evident across a range of topics such as brain anatomy, physiology, and development (Figure 1C). Importantly, these subjective ratings did not just increase after BrainU 101, but rather every time they encountered the material, in BrainU 202 or 303 and in their own classrooms. This demonstrates that participating teachers were not just walking through canned lessons but were actively engaged and still growing as neuroscientists. As one teacher stated, "every time I took a brain class I keep building on what I learned and then when I went back to teach about it the unit got better and better." The increased teacher knowledge after BrainU 101 was also reflected in their increased confidence to teach a range of neuroscience topics (Figure 1D). A previous study demonstrated that these teacher content knowledge gains translated to gains in student knowledge related to how the brain works, how to maintain brain health, and how to design and conduct scientific experiments (MacNabb et al., 2006b).

Moreover, improvements in teachers' student-centered pedagogical practices were observed in classroom practice. Classroom observations utilized two measures of pedagogical quality in classrooms of both BrainU teachers and a comparison group of middle school life science teachers that was recruited by the evaluator, and did not receive BrainU training (for more details, see Roehrig et al., 2012). Comparison teachers were experienced, as were BrainU teachers. Their classrooms included comparable arrangements, resources, and student populations. Additional comparisons were made to published data from a national group of control teachers (Roehrig et al., 2012). The first measure was the Standards of Authentic Classroom Instruction, developed to evaluate the depth of intellectual involvement in social science classes (Lawrenz, Huffman, & Gravely, 2007; Newmann, Secada, & Wehlage, 1995). The Standards addressed four broad characteristics of classroom engagement and student thinking relevant to all K–12 subject areas, not just science classrooms. *Higher-order thinking* is when students combine facts and ideas to synthesize, generalize, explain, hypothesize, or arrive at a

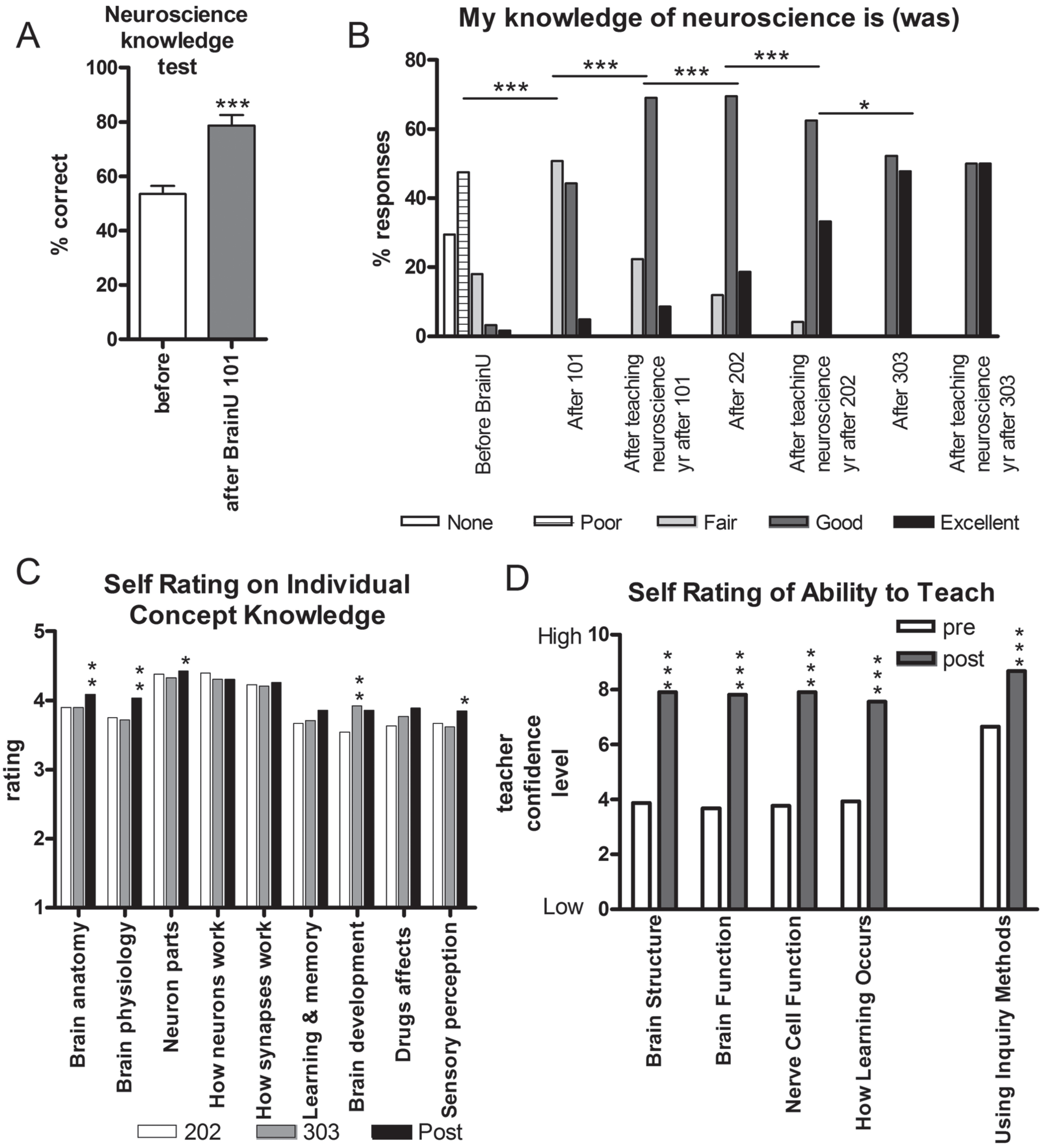

FIGURE 1. *BrainU teacher content knowledge assessment and self-ratings of neuroscience knowledge. (A) Teacher content knowledge was assessed using an 11-question multiple-choice test given at the beginning and end of a BrainU workshop. Bars represent* M ± SEM *across* $n = 5$ *separate workshops. (B) Teacher survey ratings of their own general knowledge of neuroscience before and after different BrainU workshops. Numbers of surveys tallied, from left to right,* $n = 61, 61, 58, 59, 59, 23,$ *and 21. Asterisks represent* p *values for two-tailed* t*-test comparisons of successive assessment points, ****$p < .001$*, **$p < .05$*. (C) Teacher survey ratings of their own knowledge on specific neuroscience concepts after BrainU 202, BrainU 303, and after teaching for 1 year post BrainU 303. Number of surveys tallied at each time were* $n = 52, 39,$ *and 35, respectively. Asterisks represent* p *values for two-tailed* t*-test comparisons of mean ratings compared to the bar to the immediate left, ***$p < .01$*, **$p < .05$*. (D) Teacher survey ratings of their own ability to teach specific neuroscience concepts and using inquiry pedagogy (****$p < .001$*). A, Reprinted from "Neuroscience Education of preK–12 Teachers," by J. M. Dubinsky, 2010,* Journal of Neuroscience, 30*, pp. 8057–8060. D, Reprinted from "Neuroscience in Middle Schools: A Professional Development and Resource Program That Models Inquiry-Based Strategies and Engages Teachers in Classroom Implementation," by C. MacNabb, L. Schmitt, M. Michlin, I. Harris, L. Thomas, D. Chittendon, . . . J. M. Dubinsky, 2006,* CBE—Life Sciences Education, 5*, pp. 144–157.*

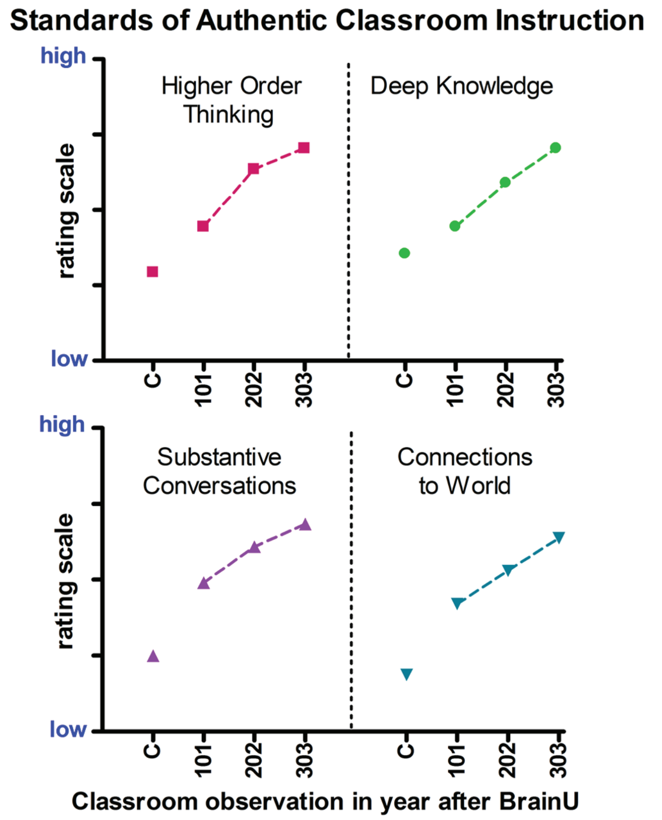

FIGURE 2. *Classroom observation ratings of Standards of Authentic Classroom Instruction. Average ratings of comparison teachers' (C) classrooms (*$n = 12$*) and BrainU 101, 202, and 303 teachers' classrooms (*$n = 46, 28,$ *and 11, respectively). Linear regressions on the mean ratings within each standard produced slopes significantly different from 0. A one-way ANOVA comparing the four regression slopes was not significant, indicating that the increasing ratings across levels of BrainU were comparable for all four measures. After BrainU 101 attendance, performance on all standards except deep knowledge increased compared to controls, with* $p < .01$ *(two-tailed* t *test), and with effect sizes (Cohen's* d*) of 0.74–1.00. The difference was even more striking after BrainU 303, with performance on all standards increasing compared to controls, with* $p < .001$ *on all standards and effect sizes of 1.81–2.23.*

conclusion, and it was distinguished from lower-order thinking involving repetitive receiving or reciting of factual information, rules, and algorithms. *Depth of knowledge* was assessed as the degree to which instruction and students' reasoning addressed the central ideas with enough thoroughness to explore connections and relationships and to produce relatively complex understandings and explanations. *Substantive conversations* tracked extended (at least three consecutive) conversational interchanges among students and the teacher in a way that built an improved and shared understanding of ideas or topics. *Connections to the world* measured students' involvement and ability to connect substantive knowledge to public problems or personal experiences. Observations of participants' classrooms and those of control teachers who did not attend BrainU demonstrated that the cognitive engagement among students and teachers also improved (Figure 2). Observer assessment of each of these characteristics increased significantly after BrainU 101 (Figure 2). With each successive BrainU professional development workshop, teachers continued to improve their ability to engage students and stimulate deep thinking in discussions pertaining to science.

The second measure was the Classroom Observation Protocol (COP) developed to evaluate the implementation of inquiry methods (Lawrenz, Huffman, & Appeldoorn, 2002). Although designed specifically for use in science and mathematics classrooms, the nine key indicators on the COP (see Table 4) are reflective of good teaching practices for any subject. Measures of these nine key indicators of reform pedagogy from BrainU teachers' classrooms exceeded those of both local and national control teachers, often by a full standard deviation (Table 4). Unlike the progressive change in the Standards ratings, observer ratings on the Key Indicators did not increase further after BrainU 202 or 303, indicating that these practices accompany the first level of implementing inquiry. Turning to the Likely Effect of the Lesson, raters' projections were elevated in all BrainU classrooms compared to controls after the first year. These observations are consistent with students' end of the school year reports of having maintained an interest in the brain activities, increased their interest in science and confidence in their scientific ability, and favorably remembered the brain unit (MacNabb et al., 2006b).

BrainU's long-term success was not attributable to self-selection of teachers. No differences were observed in performance on the pre- or post-workshop content test when teachers who only took BrainU 101 were compared with those that continued in the program (pretest, posttest scores [$M \pm SD$] for 101 only: 52.2% ± 16.1%, 80.9% ± 10.5%; for continuing teachers: 52.7% ± 15.1%, 75.9% ± 12.2%). The teachers who did not continue reported less confidence in their neuroscience knowledge at the end of BrainU 101 (7.75 ± 1.02 for continuing teachers; 6.91 ± 0.88 for 101-only teachers), $t(46) = 2.93$, $p = .005$. Not enough teachers who did not continue were observed to make reliable comparisons on these scales. Observation scores of noncontinuing teachers on the Standards of Authentic Instruction were, however, on the higher end of the range of scores on each standard and within range on the other measures. Thus, teachers did not drop out of the program because of an inability to learn the material or ability to apply inquiry-based pedagogies in their classrooms.

Implications

We conjecture that the underlying message of BrainU—that synaptic plasticity is the basis of learning and memory—is inherently proactive and hopeful, and potentially motivates teachers and their students to attend to and participate in the learning process. Perhaps the most striking evidence for this conjecture is that following BrainU 101, teachers allocated 1–4 *additional* weeks of instruction on the nervous system, with two-thirds reporting 2+ additional weeks of instruction.[2] Although evidence for this conjecture is difficult to isolate from classroom performance data, teachers' reflections during and after BrainU provide additional insights into the motivational value of the

Table 4
Comparison of BrainU Classroom Ratings on Classroom Observation Protocol Key Indicators and Likely Effect of the Lesson With Classrooms in Minnesota Not Involved in BrainU and to Control Classrooms in the CETP program (cCETP) (Lawrenz et al., 2003)

	BrainU vs. MN controls		BrainU vs. cCETP	
	p	*d*	*p*	*d*
Key indicators				
Lesson encouraged students to seek and value alternative modes of investigation or problem solving	.003	0.94**	<.001	1.81***
Students were encouraged to generate conjectures, alternative solution strategies, and ways of interpreting evidence.	.006	0.95**	<.001	1.29***
Lesson promoted strongly coherent conceptual understanding.	.002	0.96**	<.001	0.77***
Elements of abstraction were encouraged when it was important to do so.	.001	1.10***	<.001	0.84***
Instructional strategies and activities respected students' prior knowledge and misconceptions	<.001	1.16***	<.001	0.73***
Teacher displayed an understanding of science concepts.	.007	0.93**	.097	0.32
Appropriate connections were made to other areas of science, to other disciplines, and/or to real-world contexts, social issues, and global concerns.	.001	1.16***	<.001	0.96***
Interactions reflected collaborative working relationships among students and between teacher and students.	.002	0.92**	<.001	1.12***
Students were reflective about their learning.	<.001	1.25***	<.001	1.19***
Likely effect of the lesson				
On students' understanding and capacity to carry out own inquiries	.001	1.17***	<.001	1.71***
On students' understanding of important science concepts	.001	0.96***	<.001	0.78***
On students' understanding of science as a dynamic body of knowledge generated and enriched by investigation	.003	0.95***	<.001	1.40***

Note. BrainU classroom exceeded both comparison sets on all rated, Likert-type scale measures. Only one comparison was not statistically significant. Statistical calculations (two-tailed *t* tests, *p* values, effect sizes or Cohen's *d*) were performed on 85 BrainU, 12 MN comparison, and 48 cCETP classrooms. MN = Minnesota. Data from control classrooms in the CETP program reproduced with permission of Dr. Frances Lawrenz. CETP data from: http://www.cehd.umn.edu/carei/publications/#technology.
$^{**}p < .01$, $^{***}p < .001$.

concept of synaptic plasticity. BrainU teachers were more self-aware of how their own teaching behaviors had the capacity to change students' brains as students experienced, modeled, utilized, and constructed their own knowledge. As an example of how neuroscience content knowledge influenced teaching strategies, teachers indicated they would change their teaching strategies and implement more active, student-centered lessons. Knowledge of the biological basis of learning and memory and the inherent plasticity of this intricate system gave teachers a more positive attitude towards each student's ability to change and learn. They communicated that this was a powerful explanation that their students needed to understand as well. Teachers felt empowered that they could provide students with an explanation for why practice and application were necessary to consolidate learning. Teachers felt their knowledge of brain maturation increased their ability to be patient and encouraging with students' impulsivity, indecisiveness, and other life stresses. They understood better how stress in students' backgrounds could influence their biological starting points for learning and performing in school. Teachers expressed more personal motivation to try to reach students. Neuroscience knowledge bolstered their belief in education: They expressed a desire to teach neuroscience to their students, to pass on what they felt to be ideas that would motivate students to try. Although anecdotal, these powerful ideas reveal the promise of neuroscience for providing meaningful classroom learning experiences, informing teacher practice and strengthening teacher–student connections.

It is important to note that pedagogical changes and teaching of neuroscience were not limited to the life science teachers who attended BrainU. Teachers from other scientific and non-scientific disciplines also incorporated the teaching of neuroscience into their classrooms. For example, teachers used brain plasticity as a topic for discussion in their home-room and AVID classes to help students understand their own role in the learning process. To take another example, one English teacher taught neuroscience as part of understanding the challenges faced by characters with disabilities in novels and texts students read in her class.

Because BrainU modeled best practices in inquiry pedagogy, we cannot separate the impact of the neuroscience content that was taught from the way it was taught. This raises a number of important questions for future research to disentangle method and content. Teaching neuroscience using a teacher-centered, lecture approach would be unconscionable considering best practices for professional development and K–12 science teaching have been established. BrainU focused on the neurobiology of learning—on plasticity. It is an open question whether this is “the best” level to conceptualize learning. Would teachers show comparable or different (smaller? larger?) changes following a workshop focused on brain function more generally? On psychological principles of learning? On principles emanating from the learning sciences? In addition to the behavior changes observed in BrainU classrooms, are there concomitant improvements in measures of student learning (e.g., science grades, science achievement test scores)? Future research is required to isolate the aspects of BrainU that produced positive impacts, and to compare those impacts against those produced by workshops with different theoretical underpinnings.

It is important to note that BrainU never directly addressed the question of how or whether neuroscience *should* impact the field of education. We simply taught the neuroscience learning concepts as described in Table 2. Teachers made their own connections regarding how neuroscience knowledge applied to their classrooms, if at all, and this may have strengthened their resolve to teach neuroscience content in their classrooms. On this note, we recently had BrainU teachers read and debate the set of 2009 Phi Delta Kappan papers (Jensen, 2008; Sternberg, 2008; Willingham, 2008; Willis, 2008) arguing whether neuroscience should or does influence educational practices. Teachers were surprised that this was an issue. The controversy about how neuroscience could influence classrooms described in our opening paragraph clearly was not problematic for our teachers (Hille, 2011; Pickering & Howard-Jones, 2007). Either they inherently understood the value of the topic or they had preselected themselves by their voluntary participation in BrainU, and were predisposed to want to learn about, and therefore looked favorably on, neuroscience. With respect to the second explanation, we note that in the currently ongoing BrainU, teacher participation has been at the urging of district supervisors, pulling in a less intrinsically motivated audience—and even these teachers were surprised at the controversy.

Neuroscience Learning Concepts and Pre-Service Teacher Training

Introducing new content into an established curriculum is never an easy process. The current set of coursework is always viewed as absolutely necessary with no room for covering additional material. Adding something new usually requires abandoning something old. This requires purposeful reflection, hard choices, and political compromise. However, disciplines evolve over time, and the best education requires exploring, debating, and eventually incorporating new viewpoints. For teacher preparation in the early 21st century, this debate includes whether and how to incorporate the neurobiology of learning.

University educators agree that a background in educational psychology is important information teachers need for classroom practice. Cognitive, developmental, social, affective, and moral neuroscience are now providing insights into the biological bases of behaviors studied by educational psychologists (Diamond & Amso, 2008). The mechanistic underpinnings provided by neuroscience can increase teacher understanding of and appreciation for the learning brain (Hille, 2011). If teacher educators are to ensure that the links between educational practice and neurobiology are not overstated, then schools of education will have to consider not *if*, but *how* best, to teach neuroscience concepts to pre-service teachers.

The answer to this question is surely not to send pre-service teachers to biology or neuroscience departments, where they will find large courses emphasizing mastering nervous system knowledge. The goal of such courses is to impart basic disciplinary knowledge, and not to build direct connections to teaching practice or to illustrate concepts with classroom-friendly activities. Consequently, teachers will be forced to develop or adopt their own lessons (MacNabb et al., 2006a) or rely upon canned neuroscience lessons like those provided by FOSS kits or the NIH Office of Science Education Curriculum Supplement Series. Although these may be good sources, without personal experience, discussion, and support surrounding implementation, teachers may lack the background or confidence to implement mentally engaging scientific processes in their classrooms. They may also miss the connections between the neuroscience content they teach and how neuroscientific knowledge can also improve teaching and learning.

A more thoughtful approach is to create such courses in partnerships between teacher educators and neuroscientists (Pickering & Howard-Jones, 2007). Indeed, one theme that emerged from a series of conferences on the role of neuroscience in education was the need “for a greater focus on mind and brain in initial teacher training” (Howard-Jones, 2010). BrainU provides one model of how neuroscience content can be incorporated into the training of in-service middle school science teachers. But is it also a model for introducing the neurobiology of learning into the pre-service teacher curriculum? Other cooperatively taught formats could also be envisioned. Here, we outline the opportunities and challenges of transforming pre-service teacher education along these lines.

Neuroscience is a subject area in which most pre-service teachers are unlikely to have prior exposure. In an informal review of all teacher preparation programs, public or private, in Minnesota in 2013, only 1 of 19 institutions included a neuroscience-related course among education offerings—and it addressed teaching children with brain injuries. This represents a missed opportunity, as neuroscience is well suited for *modeling* the acquisition of new knowledge by inquiry-based pedagogy. By focusing on neuroscience content and delivering it using contemporary best practices (Snyder & Lit, 2010), pre-service teachers will (a) be exposed to neurobiological concepts and mechanisms supporting the educational psychology concepts they already learn, (b) experience inquiry-based learning for themselves, (c) learn about workable classroom lesson plans that motivate students, and (d) develop the knowledge base to decide for themselves whether and how neuroscience is relevant to education. This opportunity has not gone unnoticed, and research centers at several universities across the world have adopted neuroscience as a model and are conveying some of the theoretical and practical ways that neuroscience can impact education (e.g., see Centre for Educational Neuroscience, 2008; Goswami, 2005; Hardiman, 2010; Hille, 2011).

Teachers are excellent cognitive enhancers because they change brains in ways that last a lifetime. (By contrast, coffee only temporarily improves attention!) Teachers consistently ask neuroscientists, How does the learning process work (National

Reseach Council, 2000)? Explaining what neuroscientists know about the cellular basis for synaptic change provides a context for teachers to both understand and teach about the biological basis for learning (MacNabb et al., 2006b). This knowledge is as important for elementary and early childhood teachers as it is for high school biology teachers. Prior to third grade, acquisition of initial reading and math skills is accompanied by rewiring of brain circuits. As a child or adult learns to read, areas of the left ventral temporal cortex used for recognition of faces and objects become rewired to recognize, process, and utilize letters to form and comprehend written words (Dehaene et al., 2010). As numerical and arithmetic symbols and their meaning are learned, circuits in the parietal cortex (among other areas) become engaged in processing this information (Butterworth et al., 2011). Elementary teachers provide the context for these brain changes to occur, and for this reason they need to understand both how the nervous system works and the developmental processes that shape the maturation of brain circuits. A BrainU type experience could be developed to address the needs of primary educators using curricula appropriate for young learners. Secondary school teachers must also understand that they provide the guiding experiences that build new brain circuits corresponding to different cognitive skills. Even if neuroscientists are only beginning to identify the brain areas involved in mastering sophisticated biological concepts (Draganski et al., 2006), for example, problem solving throughout educational progressions will strengthen circuits that can eventually become engaged in biology. As these examples illustrate, teachers at all grade levels benefit from understanding their efforts as providing experiences that guide and change the brains of their students.

A challenge of providing a BrainU-type experience for preservice teachers is that it will require faculty cooperation across department and college lines (Dubinsky, 2010; Goswami, 2006). Building such collaborations takes time, energy, and persistence. Navigating and overcoming administrative barriers is not easy, writing tuition-sharing agreements and calculating faculty time allotments are downright difficult. Moreover, faculty in different disciplines have different sets of pressures and priorities. Educators are arguably more balanced than scientists in their emphasis on pedagogical practice and interpersonal relationships versus content delivery. By contrast, many neuroscientists are content to lecture, in part because teaching efforts in medical schools are valued well below research productivity.[3] True collaboration will require carving out time to develop a vision of a shared teaching mission and equal participation by both educators and neuroscientists.

At the level of individual faculty, injecting neuroscience content into teacher training will require communication and cooperation among people with expertise in each area (Goswami, 2006; Howard-Jones, 2010). We have seen this firsthand: Neither neuroscientists nor science educators alone could have developed BrainU. Initially, we had to learn to speak the same language and respect each other's points of view. As highly trained critical thinkers, neuroscientists examined the initial BrainU schedule and focused on the specific scientific content to be communicated. Educators viewed the same proposal, lauding the novel content and the unique implementation strategy that aligned to overarching pedagogical goals. Although both groups were committed to the project, the educators viewed the neuroscientists as very negative and the neuroscientists viewed the educators as overly optimistic. On one hand, concepts such as excitation, inhibition, regulation, and modulation had to be explained to the science educators; on the other hand, concepts such as teaching objectives, standards, learning progressions, and scaffolding were alien to the neuroscientists. Patience was required to learn the value of what each group brought to the table, and time was required to discuss and plan the learning experiences. Educators had to stretch to understand the neurobiological concepts and scientists' critical mindset before suggesting and designing ways to convey these using minds-on or inquiry-based strategies. Neuroscientists had to struggle with how to convey information through inquiry-based instruction rather than a lecture format.

The benefit of these intensive conversations was that each faculty member became a committed partner who gained confidence in his or her own contribution to the project and learned extensively from the others. Neuroscientists' teaching skills grew immeasurably and educators gained appreciation both for what neuroscience has uncovered about our learning abilities and for its ability to motivate teachers to improve their practice. After many years and a lot of hard work from individual faculty members, the BrainU teacher training model was made to fit within the organization and intellectual structure of a traditional academic institution.

A final challenge for introducing neuroscience content into pre-service teacher education is that university-level teacher educators need to be convinced that doing so will result in preparing better classroom teachers. Frankly, this remains an open question—one with many facets. For example, neuroscience concepts are evidence that constructivist strategies have a physiological parallel, if not a direct underpinning. Modeling constructivist strategies while teaching neuroscience content provides a positive example that teachers can successfully replicate. Does the neuroscience message that synapses change with learning and that students are responsible for making this happen in their own brains motivate students sufficiently to make an observable difference in their teaching performance? Initial studies suggest that the answer to this question is "yes" (Blackwell et al., 2007). However, further research is needed on this and related questions.

Despite uncertainty about how, exactly, neuroscience can influence educational practices, the benefit of understanding how people acquire and process information has been deemed important enough to be designated a core disciplinary idea in the new Frameworks for K–12 Science Education (National Research Council, 2012). The newly released *Next Generation of Science Standards* include neuroscience in the K–12 progression (Achieve, Inc., 2013). For this reason alone, it is important that teacher educators and neuroscientists begin to work more closely on professional development and rethinking pre-service teacher education.

Conclusion

What evidence must neuroscience provide to be deemed relevant to educational practice? One answer—a detailed account of student learning at the level of synaptic activity—is problematic for many reasons. For example, it is unclear whether this description would bring more precise understanding, or whether the mass of detail would overwhelm. Another, more sophisticated answer is that neuroscience can influence education *indirectly*, through the intermediate discipline of psychology (Bruer, 1997; Varma et al., 2008). In this view, the outcomes of neuroscience experiments reinforce the prior results of psychological studies by providing biological bases or mechanistic explanations; it is the results of psychological studies that then inform education.

We believe that the second answer, though correct, is not complete. In addition to supporting psychological principles, neuroscience concepts can be used to *directly* improve teachers' understanding of student learning and development and their responsibility to shape this growth. In addition, teaching neuroscience to students can increase their self-understanding, self-efficacy, motivation, and metacognition (Blackwell et al., 2007).

The potential of this direct approach is evidenced by the success of BrainU in changing teachers' classroom practices and student attitudes. BrainU was conceived to fulfill the demands of in-service teachers for accurate, up-to-date knowledge of brain function. Directly teaching neuroscience to in-service teachers first has the effect of improving teachers' knowledge of and confidence in basic neuroscientific knowledge and research. Second, this has the effect of transforming their pedagogy—how they view student learning and therefore how they teach students. Third, teachers shared their newfound knowledge of neuroscience with their students, increasing their understanding of metacognition and their role in learning. That these gains were achieved over several weeks of workshops is incredibly promising. BrainU represents a promising start and sets the stage for future research on teaching neuroscience to in-service teachers. By contrast, the efficacy of teaching the neurobiology of learning to pre-service teachers remains largely an open question. We have introduced some of the curricular and institutional issues that it raises. We are optimistic that these issues will be addressed in the future by teacher educators and neuroscientists working together, and hopeful that this work will transform teacher preparation and professional development, and ultimately how students think about their own learning.

NOTES

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[2] This time allocation did not increase substantially following successive BrainUs. We conjecture that this was because of growing national, state and district constraints to cover *only* content defined explicitly in science standards.

[3] However, with current reductions in funding for basic research coupled with the new fiscal environment, neuroscientists may come to view contributing to teacher training as an attractive source of tuition revenue.

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