

Article

Teaching Neuroscience to Science Teachers: Facilitating the Translation of Inquiry-Based Teaching Instruction to the Classroom

G. H. Roehrig,* M. Michlin,[†] L. Schmitt,^{‡§} C. MacNabb,^{||¶} and J. M. Dubinsky^{||}

*STEM Education Center, University of Minnesota, St. Paul, MN 55108; [†]Center for Applied Research and Educational Improvement and ^{||}Department of Neuroscience, University of Minnesota, Minneapolis, MN 55455; [‡]Science Museum of Minnesota, St. Paul, MN 55102

Submitted April 13, 2012; Revised June 20, 2012; Accepted July 30, 2012
Monitoring Editor: Nancy Moreno

In science education, inquiry-based approaches to teaching and learning provide a framework for students to building critical-thinking and problem-solving skills. Teacher professional development has been an ongoing focus for promoting such educational reforms. However, despite a strong consensus regarding best practices for professional development, relatively little systematic research has documented classroom changes consequent to these experiences. This paper reports on the impact of sustained, multiyear professional development in a program that combined neuroscience content and knowledge of the neurobiology of learning with inquiry-based pedagogy on teachers' inquiry-based practices. Classroom observations demonstrated the value of multiyear professional development in solidifying adoption of inquiry-based practices and cultivating progressive yearly growth in the cognitive environment of impacted classrooms.

Current discussion about educational reform among business leaders, politicians, and educators revolves around the idea students need “21st century skills” to be successful today (Rotherham and Willingham, 2009). Proponents argue that to be prepared for college and to be competitive in the 21st-century workplace, students need to be able to identify issues, acquire and use new information, understand complex systems, use technologies, and apply critical and creative thinking skills (US Department of Labor, 1991; Bybee *et al.*, 2007; Conley, 2007). Advocates of 21st-century skills favor student-centered methods—for example, problem-based learning and

project-based learning. In science education, inquiry-based approaches to teaching and learning provide one framework for students to build these critical-thinking and problem-solving skills (American Association for the Advancement of Science [AAAS], 1993; National Research Council [NRC], 2000; Capps *et al.*, 2012).

Unfortunately, in spite of the central role of inquiry in the national and state science standards, inquiry-based instruction is rarely implemented in secondary classrooms (Weiss *et al.*, 1994; Bybee, 1997; Hudson *et al.*, 2002; Smith *et al.*, 2002; Capps *et al.*, 2012). Guiding a classroom through planning, executing, analyzing, and evaluating open-ended investigations requires teachers to have sufficient expertise, content knowledge, and self-confidence to be able to maneuver through multiple potential roadblocks. Researchers cite myriad reasons for the lack of widespread inquiry-based instruction in schools: traditional beliefs about teaching and learning (Roehrig and Luft, 2004; Saad and BouJaoude, 2012), lack of pedagogical skills (Shulman, 1986; Adams and Krockover, 1997; Crawford, 2007), lack of time (Loughran, 1994), inadequate knowledge of the practice of science (Duschl, 1987; DeBoer, 2004; Saad and BouJaoude, 2012), perceived time constraints due to high-stakes testing, and inadequate preparation in science (Krajcik *et al.*, 2000). Yet teachers are necessarily at the center of reform, as they make instructional and

DOI: 10.1187/cbe.12-04-0045

Present addresses: [§]Hamline University, St. Paul, MN 55104;
[¶]Regulatory and Clinical Research Institute, Minneapolis, MN 55416.

Address correspondence to: Janet M. Dubinsky (dubin001@umn.edu).

© 2012 G. H. Roehrig *et al.* CBE—Life Sciences Education © 2012 The American Society for Cell Biology. This article is distributed by The American Society for Cell Biology under license from the author(s). It is available to the public under an Attribution-Noncommercial-Share Alike 3.0 Unported Creative Commons License (<http://creativecommons.org/licenses/by-nc-sa/3.0>).

“ASCB®” and “The American Society for Cell Biology®” are registered trademarks of The American Society for Cell Biology.

pedagogical decisions within their own classrooms (Cuban, 1990). Given that effectiveness of teachers' classroom practices is critical to the success of current science education reforms, teacher professional development has been an ongoing focus for promoting educational reform (Corcoran, 1995; Corcoran *et al.*, 1998).

A review of the education research literature yields an extensive knowledge base in "best practices" for professional development (Corcoran, 1995; NRC, 1996; Loucks-Horsley and Matsumoto, 1999; Loucks-Horsley *et al.*, 2009; Haslam and Fabiano, 2001; Wei *et al.*, 2010). However, in spite of a strong consensus on what constitutes best practices for professional development (Desimone, 2009; Wei *et al.*, 2010), relatively little systematic research has been conducted to support this consensus (Garet *et al.*, 2001). Similarly, when specifically considering the science education literature, several studies have been published on the impact of teacher professional development on inquiry-based practices (e.g., Supovitz and Turner, 2000; Banilower *et al.*, 2007; Capps *et al.*, 2012). Unfortunately, these studies usually rely on teacher self-report data; few studies have reported empirical evidence of what actually occurs in the classroom following a professional development experience.

Thus, in this study, we set out to determine through observational empirical data whether documented effective professional development does indeed change classroom practices. In this paper, we describe an extensive professional development experience for middle school biology teachers designed to develop teachers' neuroscience content knowledge and inquiry-based pedagogical practices. We investigate the impact of professional development delivered collaboratively by experts in science and pedagogy on promoting inquiry-based instruction and an investigative classroom culture. The study was guided by the following research questions:

1. Were teachers able to increase their neuroscience content knowledge?
2. Were teachers able to effectively implement student-centered reform or inquiry-based pedagogy?
3. Would multiple years of professional development result in greater changes in teacher practices?

Current reforms in science education require fundamental changes in how students are taught science. For most teachers, this requires rethinking their own practices and developing new roles both for themselves as teachers and for their students (Darling-Hammond and McLaughlin, 1995). Many teachers learned to teach using a model of teaching and learning that focuses heavily on memorizing facts (Porter and Brophy, 1988; Cohen *et al.*, 1993; Darling-Hammond and McLaughlin, 1995), and this traditional and didactic model of instruction still dominates instruction in U.S. classrooms. A recent national observation study found that only 14% of science lessons were of high quality, providing students an opportunity to learn important science concepts (Banilower *et al.*, 2006). Shifting to an inquiry-based approach to teaching places more emphasis on conceptual understanding of subject matter, as well as an emphasis on the process of establishing and validating scientific concepts and claims (Anderson, 1989; Borko and Putnam, 1996). In effect, professional development must provide opportunities for teachers to reflect critically on their practices and to fashion new knowledge

and beliefs about content, pedagogy, and learners (Darling-Hammond and McLaughlin, 1995; Wei *et al.*, 2010). If teachers are uncomfortable with a subject or believe they cannot teach science, they may focus less time on it and impart negative feelings about the subject to their students. In this way, content knowledge influences teachers' beliefs about teaching and personal self-efficacy (Gresham, 2008). Personal self-efficacy was first defined as "the conviction that one can successfully execute the behavior required to produce the outcomes" (Bandura, 1977, p.193). Researchers have reported self-efficacy to be strongly correlated with teachers' ability to implement reform-based practices (Mesquita and Drake, 1994; Marshall *et al.*, 2009).

Inquiry is "a multifaceted activity that involves making observations, posing questions, examining books and other sources of information, planning investigations, reviewing what is already known in light of evidence, using tools to gather, analyze and interpret data, proposing answers, explanations and predictions, and communicating the results" (NRC, 1996, p. 23). Unfortunately, most preservice teachers rarely experience inquiry-based instruction in their undergraduate science courses. Instead, they listen to lectures on science and participate in laboratory exercises with guidelines for finding the expected answer (Gess-Newsome and Lederman, 1993; DeHaan, 2005). As such, teachers' knowledge and beliefs about teaching and learning were developed over the many years of their own educations, through "apprenticeship of observation" (Lortie, 1975), in traditional lecture-based settings that they then replicate in their own classrooms. To support the implementation of inquiry in K-12 classrooms, teachers need firsthand experiences of inquiry, questioning, and experimentation within professional development programs (Gess-Newsome, 1999; Supovitz and Turner, 2000; Capps *et al.*, 2012).

A common criticism of professional development activities is that they are too often one-shot workshops with limited follow-up after the workshop activities (Darling-Hammond, 2005; Wei *et al.*, 2010). The literature on teacher learning and professional development calls for professional development that is sustained over time, as the duration of professional development is related to the depth of teacher change (Shields *et al.*, 1998; Weiss *et al.*, 1998; Supovitz and Turner, 2000; Banilower *et al.*, 2007). If the professional development program is too short in duration, teachers may dismiss the suggested practices or at best assimilate teaching strategies into their current repertoire with little substantive change (Tyack and Cuban, 1995; Coburn, 2004). For example, Supovitz and Turner (2000) found that sustained professional development (more than 80 h) was needed to create an investigative classroom culture in science, as opposed to small-scale changes in practices. Teachers need professional development that is interactive with their teaching practices; in other words, professional development programs should allow time for teachers to try out new practices, to obtain feedback on their teaching, and to reflect on these new practices. Not only is duration (total number of hours) of professional development important, but also the time span of the professional development experience (number of years across which professional hours are situated) to allow for multiple cycles of presentation and reflection on practices (Blumenfeld *et al.*, 1991; Garet *et al.*, 2001). Supovitz and Turner's study (2000) suggests that it is more difficult to change classroom culture than teaching

practices; the greatest changes in teaching practices occurred after 80 h of professional development, while changes in classroom investigative culture did not occur until after 160 h of professional development.

Finally, research indicates that professional development that focuses on science content and how children learn is important in changing teaching practices (e.g., Corcoran, 1995; Desimone, 2009), particularly when the goal is the implementation of inquiry-like instruction designed to improve students' conceptual understanding (Fennema *et al.*, 1996; Cohen and Hill, 1998). The science content chosen for the professional development series described in this study was neuroscience. This content is relevant for both middle and high school science teachers and has direct connections to standards. It also is unique in that it encompasses material on the neurological basis for learning, thus allowing discussions about student learning to occur within both a scientific and pedagogical context. As a final note, it is rare for even a life science teacher to have taken any coursework in neuroscience. The inquiry-based lessons and experiments encountered by the teachers during the professional development provide an authentic learning experience, allowing teachers to truly inhabit the role of a learner in an inquiry-based setting.

STUDY

BRAIN to Middle School sought to 1) create an expert cadre of teachers who would integrate neuroscience concepts, activities, demonstrations, and experiments into their classrooms; and 2) increase teachers' use of inquiry-based teaching. The underlying premise of the program was that teachers would utilize in their own classrooms the same pedagogical approaches employed when they learned neuroscience. Thus, this study was conducted to understand the impact of a long-term, sustained professional development program on science teaching practices.

Context

We posited that providing professional development for teachers in a new content area, neuroscience, by modeling inquiry-based pedagogy would result in their adoption of similar pedagogical techniques and would improve classroom instruction. A priori, we expected that over multiple years of such professional development, teachers would become experts in both the content and process of creating and executing scientific experiments with their students. To test this premise, we developed a 3-yr series of intensive summer teacher professional development workshops combining inquiry-based pedagogy with delivery of neuroscience content taught jointly by neuroscientists and science educators. This partnership blended two very different cultures in the workshop leadership, modeling the multiple roles teachers were expected to adopt: guider in acquisition of knowledge (teacher), seeker of new knowledge (scientist), and questioner of both (everyone). Surveys and classroom observations provided data on the impact of these workshops on teachers' attitudes toward and practices of inquiry-based pedagogy and changes in the classroom cognitive environment.

Program Description. BrainU 101, BrainU 202, and BrainU 303 were each designed according to established national professional development guidelines and recommendations (Center for Science Mathematics and Engineering Education, 1996; Loucks-Horsley *et al.*, 1998; National Academy of Sciences, 2005). The summer institutes incorporated effective components of professional development: long duration, focused content built on prior knowledge, active learning, community building, voluntary participation, and alignment with state and national science standards (Garet *et al.*, 2001; National Academy of Sciences, 2005). Program activities emphasized basic neuroscience concepts appropriate for middle school audiences (MacNabb *et al.*, 2000; Society for Neuroscience, 2008). Each activity was modeled using inquiry-based instructional approaches and after each neuroscience activity, reflective discussions were used to deconstruct the instructional practices modeled by workshop staff and how these same activities might be integrated into classrooms.

Additional follow-up support was provided during the academic year. Teachers received 1–3 d of in-service coteaching from program staff in the academic years following attendance at the BrainU 101 and 202 workshops. This assistance was intended to build teacher confidence in handling brains and organisms and working in an inquiry-centered classroom. Other support included classroom supplies, a resource trunk, a school assembly program, and a classroom set of interactive exhibit stations (Science Museum of Minnesota, 2003, 2004).

The first workshop, BrainU 101, was 2 wk long. BrainU 202 and 303 each occupied a full week in successive summers. In the workshops, neuroscience was taught using a series of lessons that built successively complex understandings of brain (MacNabb *et al.*, 2006a). No textbooks were used, but primary scientific and pedagogical and secondary lay audience literature was distributed. Approximately 60% of the workshop time was spent conducting science activities and experiments; this included time to process and discuss both content and pedagogy. Science educators and scientists shared equitably in leading activities and discussions, modeling best practices, integrating their expertise, and reflecting upon one another's styles, while supporting teachers' questions. Teachers also interacted with neuroscience researchers through a series of research update lectures and laboratory tours. Classroom lesson plans incorporated a variety of hands-on, modeling, dissection, and inquiry-based activities, including open-ended, inquiry-based lessons using *Caenorhabditis elegans*, *Manduca sexta*, snails, leeches, or prism glasses (MacNabb *et al.*, 2006a). Details of the lessons have been previously reported (MacNabb *et al.*, 2006b). All lessons were mapped to Minnesota state and National Science Education Standards (Center for Science Mathematics and Engineering Education, 1996; MacNabb *et al.*, 2006a). Agendas and workshop syllabi are available online (MacNabb *et al.*, 2000).

Teachers outlined their implementation plans in a written action plan document presented at the end of each workshop. Teachers chose which lessons to incorporate into their academic year schedule, adapting the lessons and fitting neuroscience into the other required curricula wherever they saw fit.

Participants

Two complete series of the neuroscience workshops have been completed, with a total of 107 participants. The workshops were available to any science teacher in the region, although the majority of participants were teachers from the metropolitan area of the university campus. Priority was given to middle school teachers, although several upper elementary and high school teachers also participated. Participants' years of teaching experience ranged from 1 to 39 yr, with an average years of experience measuring 14.5 ± 10.6 yr. Participant schools represented a range of student populations, with average minority student populations of $50.2 \pm 30.6\%$ and free and reduced lunch rates of $43.9 \pm 41.4\%$. One hundred seven teachers completed the BrainU 101 workshop, 68 teachers completed the BrainU 101 and 202 workshops, and 41 teachers completed all three workshops. No single characteristic, previous educational attainment, school setting, subject focus, or licensure type described the majority of teachers.

For comparison, an additional group of 12 middle school science classrooms whose teachers were not involved in the BrainU program were observed at the program's conclusion. This comparison would control for any general changes in teaching practices that may have occurred during the program years. The comparison teachers were recruited from two large school districts in Minnesota. The science coordinator from each district identified several teachers who agreed to be observed. Six middle school teachers from each district, teaching life science courses or similar introductory biological science courses, were selected and observed. Thus middle school earth science, chemistry, and physics were not observed. The 12 comparison lessons observed ranged over topics including evolution, cells, genetics, environmental concepts, ecology, human biology, and classification. When observed, none of the 12 comparison teachers were teaching neuroscience. The types of activities observed in the BrainU and comparison classrooms are described below (*Pedagogical Implementation*).

Comparison teachers and their classrooms were comparable with BrainU teachers on a number of measures, despite differences on the kinds of lessons that were observed. The comparison teachers had fewer years of teaching experience on average (mean 8.1 ± 2.2); however, the comparison teachers were not inexperienced, and no comparison teacher had taught fewer than 5 yr (range 5–12 yr). Comparison schools represented a comparable range of student populations, with average minority student populations of $46.0 \pm 45.1\%$ and free and reduced lunch rates of $51.9 \pm 27.6\%$. Additionally, observer ratings of available resources and classroom arrangements were high and almost identical between the treatment and comparison groups (on a 1–3 scale: arrangement = 2.82 [treatment] and 2.83 [comparison]; resources = 2.61 [treatment] and 2.58 [comparison]; $n = 85$ [treatment] and 12 [comparison]; two-tailed *t*-test: $p = 0.89$ [resources]; $p = 0.93$ [arrangement]). In other words, availability of appropriate laboratory space, equipment, or technology was not an issue for either treatment or comparison-group teachers.

All participants voluntarily attended the workshops, having been recruited through direct mailings to schools, advertising online, and in person at teacher-oriented sites or events. BrainU teachers received \$100/wk to attend and \$500 in sup-

plies for the following academic year. Supply purchases were used for anything the teachers needed, whether related to BrainU or not. Comparison teachers received \$100 for giving us the opportunity to visit their classrooms. The University of Minnesota Institutional Review Board Protocol ruled that the program qualified as exempt (approval no. 0406E60873).

Additional comparison teacher data were obtained from the control teachers observed in the Core Evaluation of the Collaboratives for Excellence in Teacher Preparation (cCETP; controls from the CETP) program (Lawrenz *et al.*, 2002c, 2003). The CETP program compared middle school teachers trained in the use of classroom technology with those without such professional development in a nationwide National Science Foundation–sponsored program. The CETP program collected data in 2002–2003, at a time comparable with the beginning of our program. Inclusion of control teachers from this national data set provided another comparison group of teachers ($n = 48$) not trained in neuroscience. Given the relatively small size of our comparison group with respect to the treatment group, inclusion of the cCETP group provided additional context for changes registered in the current study. Similarities between the observations of Minnesota comparison teachers and those in the cCETP group demonstrate the fidelity of our observational implementation. They also permit placing the gains reported below in perspective by comparison to this national study.

Data Collection and Analysis

Content Knowledge. Teachers' neuroscience content knowledge was measured with a short pre- and posttest on neuroscience. This test consisted of 11 multiple-choice questions with five possible responses and one open-ended response item (available upon request to the corresponding author). Questions probed understanding of central nervous system processes underlying neuronal function or observable classroom behaviors; for example, "One of your students has been studying hard for a test about the brain. What changes would have occurred in the student's brain as a result of their efforts?" Because this test was designed to cover the content of BrainU 101 only, it was not administered after BrainU 202 and 303, which contained additional content.

However, at the end of each workshop (BrainU 101, 202, and 303) the teachers were also asked to complete a survey of self-assessment of their understanding of neuroscience concepts and their ability to teach these concepts. Teachers rated their level of self-confidence on a 10-point Likert scale (0 = none, 10 = high) for 11 content knowledge items, four ability-to-teach specific content items, and one ability-to-teach hands-on/inquiry-based item. Finally, teachers self-assessed their general knowledge of neuroscience on a 5-point scale (1 = none, 5 = excellent). Teachers' self-assessment of their general knowledge of neuroscience was statistically analyzed (paired-samples *t* test, two-tailed) to look for growth across each year of the BrainU program.

Classroom Observations. The classroom observation protocol was created by combining two published observation instruments: Classroom Observation Protocol (COP; Lawrenz *et al.*, 2002c) and the Authentic Classroom Instruction (Newmann *et al.*, 1995). The COP is a criterion-referenced instrument for describing and rating classroom activities in K–16

STEM settings. The protocol has several parts. The first part is a description of the general demographics of the classroom, including items such as type of course, number of students, and adequacy of the physical environment. The second part is a narrative description of the instruction, including instructional goals and a record of the instructional activity, level of student cognitive activity, and student engagement 5 and 20 min into the observation. The last two sections are evaluative ratings of the lesson and its overall quality. Included are nine key indicators, each indicator being selected as an item grounded in contemporary understandings of reform-based science instruction, as well as being predictive of standards-based instruction and positive student outcomes. Each indicator is scored on the degree to which it is evident in the observed classroom on a 1–5 scale.

The Authentic Classroom Instruction (Newmann *et al.*, 1995) assesses the quality of instruction by considering the intellectual environment of the classroom using five standards of authentic instruction: higher-order thinking, depth of knowledge, connectedness to the world beyond the classroom, substantive conversation, and social support for student achievement. Each standard is a dimensional construct scored on a 5-point scale. Higher-order thinking, in which students combined facts and ideas to synthesize, generalize, explain, hypothesize, or arrive at a conclusion, 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 about subject matter 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. Data were not collected on the fifth standard, social support for student achievement.

All observers were external to the professional development program, provided by an external evaluation team and blind to treatment condition. Observers were trained with the *Annotated Guide to the CETP Classroom Observation Protocol* (Lawrenz *et al.*, 2002a) and *A Guide to Authentic Instruction and Assessments: Visions, Standards and Scoring* (Newmann *et al.*, 1995) using the *CETP Core Evaluation Classroom Observation Videotape Guide* (Lawrenz *et al.*, 2002b). Training continued until interrater reliability reached or exceeded 90%. Observations occurred during the academic year following BrainU participation or for comparison classrooms, at the end of the study period.

Statistical Analysis

Statistical tests were chosen and reported below as appropriate for the type of data being analyzed. Independent-sample *t* tests and paired-sample *t* tests were used where appropriate. *z* tests for two independent proportions were also used. Attrition in teacher participation and survey responses over the 3 yr precluded the use of analysis of variance (ANOVA) in the data analysis, as too many data points would have needed to

be discarded. On all statistical analyses reported below, the alpha levels were always run as two-tailed. This was a conservative approach, since no theoretical reasons existed to assume directionality for one-tailed tests. Because large sample sizes can produce significant but small changes, both effect sizes (Cohen's *d*) and *p* values are reported. An effect size of 1 indicates that the mean has changed by a full SD, which is unusual in educational settings (see discussion in Deslauriers *et al.*, 2011). On several tables in which the parameters *p* and *d* appear, *p* is always the calculated *p* value, and *d* is always Cohen's *d*. The *z* tests were run on Minitab 16 software. All other tests were run on SPSS 19. Computation of Cohen's *d* was run on a Web-based calculator (www.uccs.edu/~lbecker).

RESULTS

Neuroscience Knowledge

On the neuroscience content test administered during BrainU 101, teachers initially averaged $53.6 \pm 2.9\%$ ($n = 107$ teachers) correct, which increased to $78.7 \pm 3.8\%$ ($p < 0.001$, $t = 5.25$, two-tailed for paired-sample *t* test) correct at the end of the workshop. The estimate of the effect size for this significant increase was large (Cohen's *d* = 1.5). Results from the survey of teachers' self-assessment of their own knowledge of neuroscience are shown in Figure 1. As expected, teacher knowledge increased rapidly after the BrainU 101 workshop. This self-assessed increase in knowledge corroborated the changes on the content test administered at both the beginning and end of the BrainU 101 workshop. Each time teachers addressed the material, whether in their own classrooms or in subsequent workshops, further significant increases in self-assessed knowledge gains were evident up through the

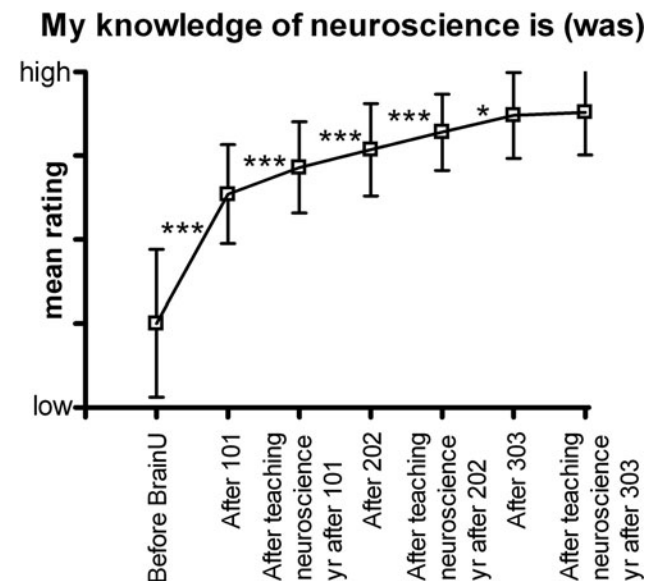


Figure 1. Teacher self-ratings of neuroscience knowledge (mean \pm SD, from left to right, $n = 61, 61, 58, 59, 59, 23$, and 21, representing an average response rate of $69 \pm 17\%$). Asterisks represent *p* values for two-tailed *t* test comparisons of mean ratings between successive assessment points. ***, $p < 0.001$; *, $p < 0.05$.

Table 1. Statistical parameters for the key indicators

Indicator	BrainU vs. comparisons		BrainU vs. cCETP	
	<i>p</i>	<i>d</i>	<i>p</i>	<i>d</i>
Lesson encouraged students to seek and value alternative modes of investigation or problem solving.	0.003	0.94	<0.001	1.81
Students were encouraged to generate conjectures, alternative solution strategies, and ways of interpreting evidence.	0.006	0.95	<0.001	1.29
Lesson promoted strongly coherent conceptual understanding.	0.002	0.96	<0.001	0.77
Elements of abstraction were encouraged when it was important to do so.	0.001	1.10	<0.001	0.84
Instructional strategies and activities respected students prior knowledge and misconceptions	<0.001	1.16	<0.001	0.73
Teacher displayed an understanding of science concepts.	0.007	0.93	0.097	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.	0.001	1.16	<0.001	0.96
Interactions reflected collaborative working relationships among students and between teacher and students.	0.002	0.92	<0.001	1.12
Students were reflective about their learning.	<0.001	1.25	<0.001	1.19

BrainU 303 workshop (Figure 1). Given that the majority of the 41 teachers who completed all 3 yr of the BrainU workshops were not biology majors, confidence in neuroscience knowledge is an important measure.

Pedagogical Implementation

Teachers devoted considerable classroom time to neuroscience. After BrainU 101, 21% spent 1–2 wk, 36% spent 2–3 wk, and 30% spent more than 4 wk. After BrainU 303, these numbers shifted slightly, so that 42% of reporting teachers spent 2–3 wk and 42% spent more than 4 wk addressing neuroscience topics in their curricula. Typically, neuroscience content was integrated within units on cells, invertebrates, or the human body.

The range of activities observed in treatment teachers' classrooms was more laboratory-based and more varied than in comparison classrooms. Multiple activities could be noted for a single class period, and data represent the percent of observed classrooms seen incorporating the indicated activity. BrainU classrooms were engaged in developing (9%) or testing (4%) hypotheses, designing experiments (9%), or collecting (42%) and analyzing and interpreting (7%) data in contrast to comparison classrooms, which only collected data (16.7%). BrainU classrooms were making models (32%), dissecting (4%), actively simulating (4%), presenting orally (6%), discussing (4%), drawing (9%), or journaling (6%), activities not observed at all in the comparison set. Comparison classrooms worked on problem solving (16.7%), learning computer software (16.7%), doing comparisons (16.7%), brainstorming or classifying (16.7%), or playing games (16.7%), activities not observed at all in BrainU classrooms. Classrooms in both groups had lectures (BrainU: 6%; comparison: 33%) or did worksheets (BrainU: 4%; comparison: 16.7%). The range of activities in the treatment classrooms represented more time spent on active experimentation and involved more higher-order thinking, whereas students in comparison-group classrooms most often experienced lectures or individual, student-focused activities.

The ratings on the nine key indicators observed for BrainU teachers after the 101 workshop were significantly higher than those for the comparison-group teachers (Table 1 and Figure 2). Treatment teachers performed significantly better than comparison teachers on all of the nine key indicators. These key indicators corroborated the changes observed on the Standards of Authentic Instructions (see *Classroom Intellectual Environment*), with most of the improvement occurring after BrainU 101.

In addition, observers gave each classroom an overall rating on the likely effect of the lesson on student understanding of scientific process as well as content and students' ability to carry out a classroom investigation (Figure 3 and Table 2). Treatment classrooms scored significantly higher than the comparison classrooms on all three of these measures. Similar to the rating of key indicators, ratings on the Likely Effect of the Lesson did not improve further after the first workshop.

BrainU teachers excelled compared with the nonintervention cCETP teachers in exactly the same manner they compared with local comparison teachers (Figures 2 and 3 and Tables 2 and 3). In contrast with the local comparison teachers, the comparison teachers in the national sample displayed mastery of the content material but did not score as highly as the BrainU teachers on the other eight key indicators (Table 1). Thus, competence in content knowledge did not imply a sufficiently sophisticated set of pedagogical skills to lead students through the reasoning processes associated with experimental practices.

Classroom Intellectual Environment

Observers rated the proportion of students engaged in the activity at 5 and 20 min into the lesson (Table 3). When all observations of BrainU classrooms from all years are pooled, at 20 min, students in BrainU classrooms are significantly more engaged than in comparison classrooms. Disaggregated comparisons between BrainU teachers and comparison teachers on these measures did not reach a level of statistical significance. However, the 21–39% difference in the percent of

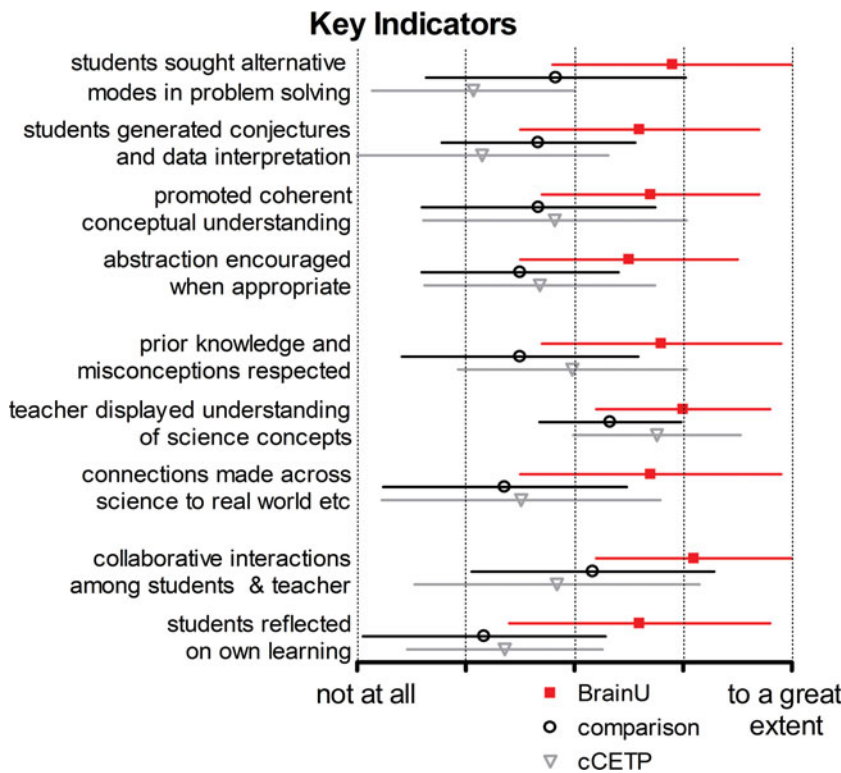


Figure 2. Classroom observation ratings of key indicators in classrooms of BrainU participants (red), comparison teachers (black), and cCETP teachers (gray). Because no significant differences were observed between observations after BrainU 101, 202, and 303 participation, all data have been aggregated. Data from comparison classrooms in the CETP program (cCETP, gray) reproduced with permission of Dr. Frances Lawrenz. Data are mean \pm SD; BrainU, $n = 85$; comparison, $n = 12$; cCETP, $n = 48$.

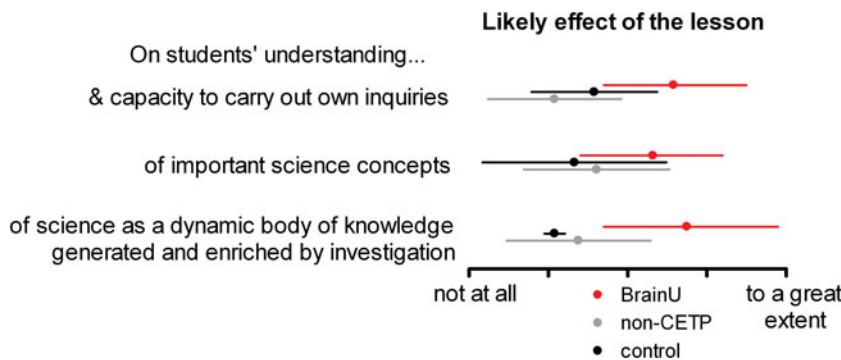


Figure 3. Classroom observation ratings of the likely effect of the lesson in classrooms of BrainU participants (red), comparison teachers (black), and cCETP teachers (gray). Because no significant differences were observed between observations after BrainU 101, 202, and 303 participation, all data have been aggregated. Data are mean \pm SD; BrainU, $n = 85$; comparison, $n = 12$; cCETP, $n = 48$.

students engaged in the lesson between BrainU and comparison classrooms is of practical importance, since more students were participating in the neuroscience lessons on a consistent basis. These data support the observations on increased cognitive activity levels (Figure 4), supporting the idea that reform pedagogy and neuroscience engage and motivate students.

Classrooms were also scored on overall cognitive engagement and indicators of inquiry-based practices using four of the five broad Standards of Authentic Instruction (Figure 4 and Table 4). The standards addressed characteristics observed in student thinking and classroom interactions: higher-order thinking, depth of knowledge, substantive conversations, and connections to the world. Teachers and their

Table 2. Statistical parameters comparing BrainU classrooms with comparison classrooms on the likely effect of the lesson

Likely effect	BrainU vs. comparisons		BrainU vs. cCETP	
	<i>p</i>	<i>d</i>	<i>p</i>	<i>d</i>
On students' understanding and capacity to carry out own inquiries	0.001	1.17	<0.001	1.71
On students' understanding of important science concepts	0.001	0.96	<0.001	0.78
On students' understanding of science as a dynamic body of knowledge generated and enriched by investigation	0.003	0.05	<0.001	1.40

Table 3. Percent of students engaged at 5 and 20 min into the observed lesson^a

Time	Teacher	<i>n</i>	<i>n</i> total	Percent classrooms engaged	<i>z</i>	<i>p</i>
5 min	Observations after BrainU 101	32	42	76	1.53	0.13
	Comparison	5	10	50		
5 min	All BrainU observations	63	79	79.7	1.81	0.07
	Comparison	5	10	50		
20 min	Observations after BrainU 101	30	42	71	1.24	0.22
	Comparison	5	10	50		
20 min	All BrainU observations	63	79	79.7	2.46	0.014
	Comparison	4	10	40		

^a*n* represents the number of classrooms in which students were engaged out of all observations (*n* total). The percent classrooms engaged measure represents the proportion of classes in which students were engaged at that time point. *p*, *z*, two-tailed *z*-test on independent proportions vs. comparisons.

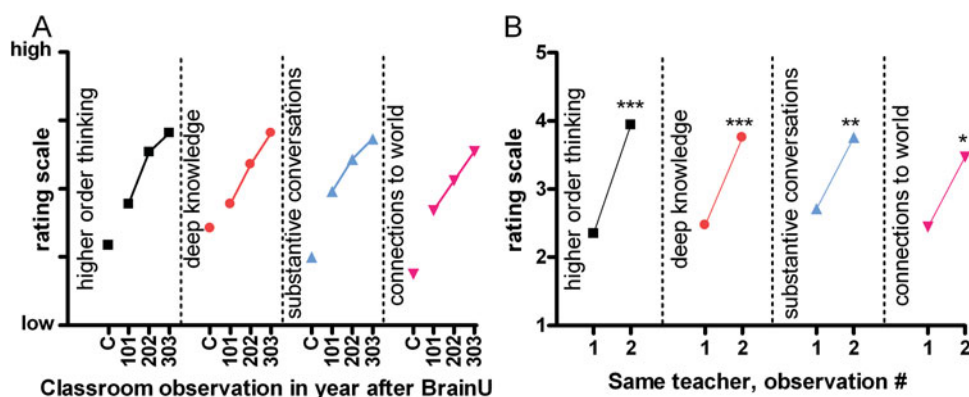


Figure 4. Classroom observation mean ratings of Standards of Authentic Classroom Instruction in comparison teachers' (C) or BrainU 101, 202, and 303 participants' classrooms. (A) Observation ratings by years of BrainU attendance. SD ranges were 0.75–1.16 for BrainU teachers and 0.58–0.95 for comparison teachers; comparison classrooms, $n = 12$; BrainU 101 classrooms, $n = 46$; BrainU 202 classrooms, $n = 28$; and BrainU 303 classrooms, $n = 11$. Linear regressions on the mean ratings within each standard produced slopes significantly different from 0 (higher-order thinking, $p = 0.014$; deep knowledge, $p = 0.004$; substantive conversations, $p = 0.034$; connections to world, $p = 0.021$). A one-way ANOVA comparing the slopes was not significant, indicating the rates of change in each of these parameters were equal. For additional *t* test *p* values and Cohen's *d* effect sizes, see Table 4. (B) Two observations of the same teacher. Seventeen teachers were observed in the academic years after successive BrainUs. *, $p < 0.05$; **, $p < 0.01$; *** $p < 0.001$ in two-tailed *t* tests.

classrooms improved steadily on each of the four standards of reform-based teaching with each successive year in the program (Figure 4 and Table 4). In the academic year after the BrainU 101 workshop, all observed participants improved their classroom climates substantially over those observed for teachers not in the program. The dramatic improvement in the cognitive environment indicated by these four Standards of Authentic Instruction was not related to teaching experience, as regressions of ratings of each standard on years taught yielded correlation coefficients approaching zero for both comparison and BrainU teachers.

DISCUSSION

Sustained Professional Development Impacts Classrooms

This study was guided by our interest in developing a culture of inquiry-based science instruction in secondary science classrooms. While our primary focus was on increasing and improving the instruction of neuroscience concepts, an equally important focus was improving the quality of inquiry-based instruction. The results of the study indicate that sustained, inquiry-based science professional

Table 4. Statistical parameters for classroom observations of Standards of Authentic Classroom Instruction

Standard	Comparison vs. BrainU 101		BrainU 101 vs. 202		BrainU 202 vs. 303		BrainU 101 vs. 303		Comparison vs. BrainU 303	
	<i>p</i>	<i>d</i>	<i>p</i>	<i>d</i>	<i>p</i>	<i>d</i>	<i>p</i>	<i>d</i>	<i>p</i>	<i>d</i>
Higher-order thinking	0.01	0.74	0.004	0.73	0.408	0.29	0.003	1.01	<0.001	2.23
Deep knowledge	0.192	0.42	0.029	0.55	0.156	0.47	0.001	1.24	<0.001	1.81
Substantive conversations	0.006	1.03	0.057	0.47	0.345	0.32	0.012	0.92	<0.001	1.98
Connections to world	0.001	1.00	0.113	0.39	0.296	0.39	0.038	0.76	<0.001	1.98

development can positively impact the quality of science teaching and that teachers engaged their students in frequent, high-quality, investigative neuroscience activities.

Following BrainU 101, teachers significantly improved their content knowledge of neuroscience. The fact that few teachers scored perfectly on the test indicates that the exam was challenging and had enough range to capture their true knowledge gains. Teachers' confidence in their neuroscience knowledge and their ability to teach neuroscience continued to show statistically significant increases following the formal professional development as teachers implemented lessons with staff support. As noted in previous studies (Loucks-Horsley and Matsumoto, 1999; Loucks-Horsley *et al.*, 2003; Haslam and Fabiano, 2001), classroom follow-up is a critical component of effective professional development, as indicated by these continued improvements in teacher confidence about their abilities to teach neuroscience.

Classroom observations following BrainU 101 indicated teachers not only implemented neuroscience lessons in their courses, but they adopted many of the techniques of reform pedagogy. BrainU teachers had fewer traditional practices (lecture, worksheet, etc.) and more laboratory experiences for students. It is important to note that while both BrainU and comparison teachers provided opportunities for students to collect data, only BrainU teachers also provided opportunities for students to design their own experiments, develop their own hypotheses, analyze and interpret data, and present their findings. BrainU teachers' practices included all five essential features of inquiry (NRC, 2000). When considering the quality of these laboratory experiences, BrainU teachers scored significantly higher on indicators of inquiry-based instruction than either group of comparison teachers. As with previous research studies (Shields *et al.*, 1998; Weiss *et al.*, 1998; Supovitz and Turner, 2000; Banilower *et al.*, 2007), we found that sustained (80 h with classroom follow-up), transformative professional development can significantly impact teachers' classroom practices and create a more inquiry-based, investigative classroom culture. Critically, our study provides observational data to support these claims, as opposed to teacher self-report data used in previous studies (e.g., Supovitz and Turner, 2000; Banilower *et al.*, 2007).

The longitudinal structure of the three BrainUs, plus the additional in-service support, far exceed the time frame of most professional development programs. The additional hours of immersion, practicing and discussing the meticulous process of extracting knowledge from experimental manipulations and measurements, resulted in acquisition of an enriched pedagogical skill set and the ability to lead others through the scientific process. These observations captured how the rapidly adopted inquiry-based teaching practices grew into steadily increasing gains in student cognitive participation over multiple years of teacher professional development and implementation. The significant gains following BrainU 202 and 303 in the intellectual environment of the classroom demonstrate that professional development hours beyond the first year were critical to moving beyond "mechanistic" implementation of classroom activities to a more intellectual climate around scientific investigations. Revisiting and extending neuroscience and pedagogical concepts in BrainU 202 and 303 provided teachers the opportunity to reflect upon their experiences and make plans for further improving their

teaching. The continuous encouragement and sharing of experiences with colleagues and BrainU staff reinforced and strengthened individual teachers' implementations.

As previously noted (Supovitz and Turner, 2000; Garet *et al.*, 2001; Desimone, 2009; Capps *et al.*, 2012), extended professional development is necessary to change classroom climate, to move inquiry-based experiences beyond a focus on data collection to one in which substantive conversations are occurring around data and concepts, and to develop deep conceptual understanding, rather than surface-level content knowledge. Concentrated, longitudinal professional development focused on specific instructional practices increases their use in classrooms and active-learning opportunities produce further additive effects (Desimone *et al.*, 2002). But results from these interventions can be varied. In one study in which elementary teachers attended a 1-d/wk intensive professional development in constructivist science practices that they immediately implemented, significant improvement on a survey of teacher knowledge and practices was observed, but the effect size was 0.16 (Diaconu *et al.*, 2012). In contrast, elementary teachers involved in more than 300 h of science professional development using standard educational kits and curricula also showed improvement when their classrooms were observed on the Newmann Authentic Pedagogy rating scales, but not to the extent registered by BrainU teachers (Corcoran *et al.*, 2003). Highly successful 2-yr teacher professional development has reported large effect sizes on increased student unit test performance when the professional development focused on promoting positive teacher beliefs regarding students' abilities (Lee *et al.*, 2008). Our neuroscience message emphasizing brain plasticity may have had a similar effect, convincing teachers of students' potential capabilities.

Contemporary pedagogical theory hypothesizes that inquiry-based pedagogy improves students' 21st-century skills (Donovan and Bransford, 2005; Desimone, 2009). Our data demonstrate that the use of inquiry-based pedagogy during sustained and intensive professional development improves the intellectual climate in the classroom. Thus, investing in intensive, supportive, inquiry-based science teacher professional development within a content domain provides a clear pathway toward improving K-12 educational outcomes. Most importantly, our data emphasize the time it takes for teachers to develop the knowledge and confidence to practice these skill sets in their classrooms. This is particularly important in light of a recent report concluding that there is a decline in the intensity of professional development opportunities for teachers and that teachers nationwide have fewer opportunities to engage in sustained (greater than 8 h in duration) professional development than 4 yr ago (Wei *et al.*, 2010).

Study Limitations

When attending their first BrainU, teachers were not anticipating an extended multiyear time investment. The successive years of professional development grew out of demand by teachers in a previous set of workshops for more opportunities to learn additional neuroscience (MacNabb *et al.*, 2006b). Indeed, the majority of teachers did not complete 3 yr of professional development. We have to assume that some degree of self-motivation characterized the

teachers, since attendance was voluntary and the monetary reward was minimal. Presumably, teachers returned because they enjoyed the process and felt it benefited their practices. Future investigations of teacher motivation in attending professional development may shed light on what teacher and/or workshop qualities kept them coming back. As in any educational study, increasing the numbers of hours teachers participate will improve outcomes (Banilower *et al.*, 2006).

We cannot rule out the influence of other professional development experiences encountered by both BrainU and comparison teachers over a multiyear program. Some teachers did report regularly attending summer programs. Scheduling was an issue influencing the return of others. However, these issues were as likely to impact the comparison teachers as much as the BrainU teachers. To minimize any effects of changing expectations for teacher attendance at professional development events over the course of the many years of data collection, observers evaluated the comparison teachers after all BrainU classroom observations were completed. Changing district expectations should therefore have influenced both groups comparably.

Impact of Neuroscience

The critical factors contributing to the success of the neuroscience program included the inquiry-based, collegial format of the workshops, the neuroscience content, and the combined skills of the team that ran the program. Because neuroscience is a biological science not normally included in life sciences degree programs, adopting the inquiry-based practices may be easier in the context of a new discipline. Struggling with the material themselves enabled teachers to understand points at which students might also need guidance. For traditional topics in biology, chemistry, and physics, teachers may have to unlearn the traditional way they acquired their own knowledge before they can adopt inquiry-based practices.

Neuroscience also provides a scientific framework for approaching and comprehending what makes for effective teaching (Howard-Jones, 2010). Understanding the basic neurobiology of learning at the synaptic and circuit levels and the integration of salience and emotional responses into learning and decision making informs teachers about the most fundamental aspects of the learning process. This knowledge reinforces teachers' intuition about what makes a lesson motivating and memorable for students. Understanding that they are responsible for changing their own synapses and turning on the genes that strengthen those synapses empowers middle school students to apply themselves in school (Blackwell *et al.*, 2007). For the adults structuring the environments that guide student learning, understanding these same basic neuroscience concepts may encourage teaching strategies that develop independent student thinking. Teachers made these connections for themselves; we did not explicitly focus on this topic. Future investigations of teacher motivation and comparative observations of the outcomes of in-depth teacher professional development across scientific disciplines will be necessary to separate the impact of neuroscience knowledge from that of the sustained and intensive professional development format.

CONCLUSION

The impact of the BrainU program was its profound influence on teachers. BrainU uniquely combined all the established components of high-quality professional development (Desimone, 2009; Capps *et al.*, 2012) with a topic that was highly motivating and relevant to both the practice of teaching and to its intellectual underpinnings. By experiencing and practicing inquiry as they learned neuroscience themselves, teachers understood how to structure these activities for their students to maximize learning. When asked to comment upon what they took home from their BrainU experience, teachers consistently remarked upon their deepened appreciation and application of inquiry-based pedagogy. The observational nature of this study provided a documented, causal link between high-quality professional development and changes in classroom practices.

ACKNOWLEDGMENTS

We thank Dr. Frances Lawrenz for her permission to use the cCETP data for comparison purposes. We acknowledge the contributions of the staff from the Science Museum of Minnesota: Larry Thomas, Leisl Chatman, Keith Braafladt, Jennifer Teegarden, Teresa Hung, Kristen Murray, Sarah Hick, Jeff McLennan, Dawn Cameron, David Chittendon, Maija Sedzielarz, and Jim Heintzman, in the instruction of pedagogy portions and development of resources for the workshops. Additional program instructional and teacher support staff included Amber Clausen, Georgia Brier, Nicole Drager, and Kelly Casperson. Thanks also go to all the faculty who provided research update lectures and/or opened their research laboratories for tours during a BrainU: Timothy J. Ebner, M.D., Karen Mesce, Ph.D., Kathleen Klukas, Ph.D., Jocelyn Shaw, Ph.D., Peter Santi, Ph.D., Monica Luciano, Ph.D., Kathleen Zahs, Ph.D., and Walter Low, Ph.D.

This work was supported by funding from the National Institutes of Health, National Center for Research Resources, Science Education Partnership Award R25 RR17315, and the University of Minnesota Medical School, University of Minnesota Academic Health Center.

REFERENCES

- Adams PE, Krockover GH (1997). Concerns and perceptions of beginning secondary science and mathematics teachers. *Sci Educ* 81, 29–50.
- American Association for the Advancement of Science (1993). Project 2061 Benchmarks. Washington, DC. www.project2061.org/publications/bsl/online/bolintro.htm (accessed 13 April 2012).
- Anderson CW (1989). The role of education in the academic disciplines in teacher education. In: Research perspectives on the graduate preparation of teachers, ed. A Woolfolk, Englewood Cliffs, NJ: Prentice Hall, 88–107.
- Bandura A (1977). Self-efficacy: toward a unifying theory of behavioral change. *Psychol Rev* 84, 191–215.
- Banilower ER, Boyd SE, Pasley JD, Weiss IR (2006). Lessons from a Decade of Mathematics and Science Reform. A Capstone Report on the Local Systemic Change through Teacher Enhancement Initiative, Chapel Hill, NC: Horizon Research. www.pdmathsci.net/reports/capstone.pdf (accessed 13 April 2012).
- Banilower ER, Heck DJ, Weiss IR (2007). Can professional development make the vision of the standards a reality? The impact of the National Science Foundation's Local Systemic Change through Teacher Enhancement Initiative. *J Res Sci Teach* 44, 375–395.

- Blackwell LS, Trzesniewski KH, Dweck CS (2007). Implicit theories of intelligence predict achievement across an adolescent transition: a longitudinal study and an intervention. *Child Dev* 78, 246–263.
- Blumenfeld P, Soloway E, Marx RW, Guzdial M, Palincsar A (1991). Motivating project-based learning: sustaining the doing, supporting the learning. *Educ Psychol* 26, 369–398.
- Borko H, Putnam RT (1996). Learning to teach. In: *Handbook on Educational Psychology*, ed. RC Calfee and D Berliner, New York: Macmillan, 673–708.
- Bybee RW (1997). Achieving scientific literacy: from purposes to practices, Portsmouth, NH: Heinemann.
- Bybee RW, van Scotter PG, Simon BD (2007). *A Decade of Action: Sustaining Global Competitiveness. A Synthesis of Recommendations from Business, Industry, and Government for a 21st Century Workforce*. Colorado Springs, CO: BSCS.
- Capps DK, Crawford BA, Constan MA (2012). A review of empirical literature on inquiry professional development: alignment with best practices and a critique of the findings. *J Sci Teach Educ* 23, 291–318.
- Coburn CE (2004). Beyond decoupling: rethinking the relationship between the institutional environment and the classroom. *Sociol Educ* 77, 211–244.
- Cohen DK, Hill HC (1998). *State policy and classroom performance: Mathematics reform in California*. CPRE Policy Brief. Philadelphia, PA: University of Pennsylvania, Consortium for Policy Research in Education.
- Cohen DK, McLaughlin MW, Talbert JE (1993). *Teaching for Understanding: Challenges for Policy and Practice*, San Francisco: Jossey-Bass.
- Conley DT (2007). *Toward a More Comprehensive Conception of College Readiness*, Eugene, OR: Educational Policy Improvement Center. http://www.collegedirections.org/2007_Gates_CollegeReadinessPaper.pdf (accessed 20 September 2012).
- Corcoran T, McVay S, Riodan K (2003). *Getting It Right: The MISE Approach to professional Development*, Philadelphia, PA: University of Pennsylvania, Consortium for Policy Research in Education.
- Corcoran TB (1995). *Transforming Professional Development for Teachers: A Guide for State Policymakers*, Washington, DC: National Governors' Association.
- Corcoran TB, Shields PM, Zucker AA (1998). *Evaluation of NSF's Statewide Systemic Initiatives (SSI) Program. The SSIs and Professional Development for Teachers*, Menlo Park, CA: SRI International.
- Crawford BA (2007). Learning to teach science as inquiry in the rough and tumble of practice. *J Res Sci Teach* 44, 613–642.
- Cuban L (1990). *How Teachers Taught*, New York: Longman.
- Darling-Hammond L (2005). Teaching as a profession: lessons in teacher preparation and professional development. *Phi Delta Kappan* 86, 235–240.
- Darling-Hammond L, McLaughlin MW (1995). Policies that support professional development in an era of reform. *Phi Delta Kappan* 76, 597–604.
- DeBoer GE (2004). Historical perspectives on inquiry teaching in schools. In: *Scientific Inquiry and Nature of Science: Implications for Teaching, Learning, and Teacher Education*, ed. LB Flick and G Lederman, Dordrecht: Kluwer Academic.
- DeHaan RL (2005). The impending revolution in undergraduate science education. *J Sci Educ Technol* 14, 253–269.
- Desimone LM (2009). Improving impact studies of teachers' professional development: toward better conceptualizations and measures. *Educ Researcher* 38, 181–199.
- Desimone LM, Porter A, Garet MS, Yoon KS, Birman BF (2002). Effects of professional development on teachers' instruction: results from a three-year longitudinal study. *Educ Eval Policy Anal* 24, 81–112.
- Deslauriers L, Schelew E, Wieman C (2011). Improved learning in a large-enrollment physics class. *Science* 332, 862–864.
- Diaconu DV, Radigan J, Suskavcevic M, Nichol C (2012). A multi-year study of the impact of the Rice Model Teacher Professional Development on elementary science teachers. *Int J Sci Educ* 34, 855–877.
- Donovan MS, Bransford JD (2005). *How Students Learn: Science in the Classroom*, Washington, DC: National Academies Press.
- Duschl RA (1987). Abandoning the scientific legacy of science education. *Sci Educ* 75, 51–62.
- Fennema E, Carpenter TP, Franke ML, Levi L, Jacobs VR, Empson SB (1996). A longitudinal study of learning to use children's thinking in mathematics instruction. *J Res Math Educ* 27, 403–434.
- Garet MS, Porter AC, Desimone L, Birman BF, Yoon KS (2001). What makes professional development effective? Results from a national sample of teachers. *Am Educ Res J* 38, 915–945.
- Gess-Newsome J (1999). Pedagogical content knowledge: an introduction and orientation. In: *Examining Pedagogical Content Knowledge*, ed. J Gess-Newsome and NG Lederman, Dordrecht: Kluwer Academic.
- Gess-Newsome J, Lederman NG (1993). Pre-service biology teachers' knowledge structures as a function of professional teacher education: a year-long assessment. *Sci Educ* 77, 25–45.
- Gresham G (2008). Mathematics anxiety and mathematics teacher efficacy in elementary pre-service teachers. *Teach Educ* 19, 171–184.
- Haslam BM, Fabiano L (2001). *A Comprehensive Review of Professional Development in South Carolina*, Washington, DC: Policy Studies Associates.
- Howard-Jones PA (2010). *Introducing Neuroeducational Research: Neuroscience, Education and the Brain from Contexts to Practice*, Abingdon, Oxon, UK: Routledge.
- Hudson SB, McMahan KC, Overstreet CM (2002). *The 2000 National Survey of Science and Mathematics: Compendium of Tables*, Chapel Hill, NC: Horizon Research. http://horizon-research.com/reports/report.php?report_id=13 (accessed 20 September 2012).
- Krajcik J, Mamlock R, Hug B (2000). Modern content and the enterprise of science: science education in the twentieth century. In: *Education across a Century: The Centennial Volume. One-Hundredth Yearbook of the National Society for the Study of Education*, ed. L Corno, Chicago: University of Chicago Press, 205–237.
- Lawrenz F, Huffman D, Appeldoorn K (2002a). *Annotated Guide to the CETP Classroom Observation Protocol*, Minneapolis: Center for Applied Research and Educational Improvement, College of Education and Human Development, University of Minnesota. <http://physicalscience56.wikispaces.com/file/view/AnnotatedGuideCOP.pdf> (accessed 20 September 2012).
- Lawrenz F, Huffman D, Appeldoorn K (2002b). *CETP Core Evaluation Classroom Observation Videotape Guide*, Minneapolis: Center for Applied Research and Educational Improvement, College of Education and Human Development, University of Minnesota.
- Lawrenz F, Huffman D, Appeldoorn K (2002c). *Classroom Observation Handbook. CETP Core Evaluation—Classroom Observation Protocol*, Minneapolis: Center for Applied Research in Educational Improvement, College of Education and Human Development, University of Minnesota.

- Lawrenz F, Michlin M, Appeldoorn K, Hwang E (2003). CETP Core Evaluation: Project Publications.
- Lee O, Deaktor R, Enders C, Lambert J (2008). Impact of a multiyear professional development intervention on science achievement of culturally and linguistically diverse elementary students. *J Res Sci Teach* 45, 726–747.
- Lortie DC (1975). *School Teacher: A Sociological Study*, Chicago: University of Chicago Press.
- Loucks-Horsley S, Hewson PW, Love N, Stiles K (1998). *Designing Professional Development for Teachers of Science and Mathematics*, 1st ed., Madison, WI: National Institute for Science Education.
- Loucks-Horsley S, Love N, Stiles K, Mundry S, Hewson PW (2003). *Designing Professional Development for Teachers of Science and Mathematics*, 2nd ed., Thousand Oaks, CA: Corwin Press.
- Loucks-Horsley S, Matsumoto C (1999). Research on professional development for teachers of mathematics and science: the state of the scene. *Sch Sci Math* 99, 258–271.
- Loucks-Horsley S, Stiles K, Mundry S, Love N, Hewson P (2009). *Designing Professional Development for Teachers of Science and Mathematics*, 3rd ed., Thousand Oaks, CA: Corwin Press.
- Loughran J (1994). Bridging the gap: an analysis of the needs of second year science teachers. *Sci Educ* 78, 365–386.
- MacNabb C, Brier G, Teegarten J, Schmitt L, Drager N, Thomas L, Dubinsky JM (2006a). Lessons. BrainU website. Resources. <http://brainu.org/lessons> (accessed 20 July 2009).
- MacNabb C, Schmitt L, Michlin M, Harris I, Thomas L, Chittendon D, Ebner TJ, Dubinsky JM (2006b). Neuroscience in middle schools: a professional development and resource program that models inquiry-based strategies and engages teachers in classroom implementation. *Cell Biol Educ* 5, 144–157.
- MacNabb C, Schmitt L, Minor S, Roehrig GH, Dubinsky JM (2000). BrainU: The Neuroscience Teacher Institute. <http://brainu.org/brainu-neuroscience-teacher-institute> (accessed 20 July 2009).
- Marshall JC, Horton R, Igo BL, Switzer DM (2009). K-12 science and mathematics teachers' beliefs about and use of inquiry in the classroom. *Int J Sci Math Educ* 7, 575–596.
- Mesquita PBD, Drake JC (1994). Educational reform and the self-efficacy beliefs of teachers implementing nongraded primary school programs. *Teach Teach Educ* 10, 291–302.
- National Academy of Sciences (2005). Resources for involving scientists in education. Choose effective approaches to staff development. www.nationalacademies.org/rise/backg4b.htm (accessed 15 July 2009).
- National Research Council (NRC) (1996). *National Science Education Standards*, Washington, DC: National Academies Press.
- NRC (2000). *Inquiry and the National Science Education Standards. A Guide for Teaching and Learning*, Washington, DC: National Academies Press.
- NRC Center for Science, Mathematics, and Engineering Education (1996). *National Science Education Standards*, Washington, DC: National Academy of Science.
- Newmann FM, Secada WG, Wehlage GG (1995). *A Guide to Authentic Instruction and Assessments: Vision, Standards and Scoring*, Madison: Wisconsin Center for Education Research.
- Porter AC, Brophy JE (1988). Good teaching: insights from the work of the Institute for Research on Teaching. *Educ Leadership* 45, 75–84.
- Roehrig GH, Luft JA (2004). Constraints experienced by beginning secondary science teachers in implementing scientific inquiry lessons. *Int J Sci Educ* 26, 3–24.
- Rotherham AJ, Willingham DT (2009). 21st century skills: the challenges ahead. *Educ Leadership* 67, 16–21.
- Saad R, BouJaoude S (2012). The relationship between teachers' knowledge and beliefs about science and inquiry and their classroom practices. *Eurasia J Math Sci Technol Educ* 8, 113–128.
- Science Museum of Minnesota (2003). Explain Your Brain. www.smm.org/schools/atyourschool/assemblies (accessed 20 July 2009).
- Science Museum of Minnesota (2004). Explorations: Change Your Brain. www.smm.org/static/explorations/changebrain.pdf (accessed 20 July 2009).
- Shields PM, Marsh JA, Adelman NE (1998). Evaluation of NSF's Statewide Systemic Initiatives (SSI) Program. The SSIs' Impacts on Classroom Practice, Menlo Park, CA: SRI International.
- Shulman LS (1986). Those who understand: knowledge growth in teaching. *Educ Researcher* 15, 4–14.
- Smith PS, Banilower ER, McMahon KC, Weiss IR (2002). *The National Survey of Science and Mathematics Education: Trends from 1977 to 2000*, Chapel Hill, N.C.: Horizon Research. <http://2000survey.horizon-research.com/reports/trends.php> (accessed 30 September 2009).
- Society for Neuroscience (2008). *Neuroscience Core Concepts. The Essential Principles of Neuroscience*, Washington, DC: Society for Neuroscience. www.sfn.org/index.aspx?pagename=core_concepts (accessed 13 April 2012).
- Supovitz JA, Turner HM (2000). The effects of professional development on science teaching practices and classroom culture. *J Res Sci Teach* 37, 963–980.
- Tyack D, Cuban L (1995). *Tinkering toward Utopia: A Century of Public School Reform*, Cambridge, MA: Harvard University Press.
- US Department of Labor (1991). *What Work Requires of Schools. A SCANS Report for America 2000*, Washington, DC. www.gsn.org/web/_shared/SCANS2000.pdf (accessed 13 April 2012).
- Wei RC, Darling-Hammond L, Adamson F (2010). *Professional Development in the United States: Trends and Challenges*. Stanford, CA: Stanford Center for Opportunity Policy in Education.
- Weiss IR, Matti MC, Smith PS (1994). *Report of the 1993 National Survey of Science and Mathematics Education*, Chapel Hill, NC: Horizon Research.
- Weiss IR, Montgomery DL, Ridgway CJ, Bond SL (1998). *Local Systemic Change through Teacher Enhancement: Year Three Cross-Site Report*, Chapel Hill, NC: Horizon Research.