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Professional Development for Technology-Enhanced Inquiry Science

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The knowledge integration framework is used to analyze studies on professional development in technology-enhanced science involving more than 2,350 teachers and 138,0000 students. The question of how professional development enhances teachers' support for students' inquiry science learning is the focus of the work. A literature search using the keywords technology, professional development, *and* science *identified 360 studies from the past 25 years, 43 of which included multiple data sources and reported results for teachers and/or students. Findings suggest that professional development programs that engaged teachers in a comprehensive, constructivist-oriented learning process and were sustained beyond 1 year significantly improved students' inquiry learning experiences in K–12 science classrooms. In professional development programs of 1 year or less, researchers encountered common technical and instructional obstacles related to classroom implementation that hindered success. Programs varied most considerably in terms of their support for teachers' use of evidence to distinguish effective technology-enhanced practices.*

Keywords: professional development, technology, science, inquiry, knowledge integration.

Leaders in education, science, and policy recognize the value of technology-enhanced inquiry materials for science and stress the importance of teacher professional development (President's Council of Advisors on Science and Technology, 2010). A recent synthesis of more than 25 meta-analytic studies investigating the role of computer-based technologies in student learning found that the teacher may play an even greater role in students' technology-enhanced learning than the nature of the technology intervention itself. The effectiveness of the technology intervention depended on the teacher's goals, pedagogy, and content knowledge (Tamin, Bernard, Borokhovski, Abrami, & Schmid, 2011). Few preservice programs prepare teachers to use technology-enhanced materials to enhance inquiry learning. As a result in-service professional development programs are the most common approach to introducing teachers to the goals and designs of technology interventions and to cultivating teachers' pedagogical content knowledge in this new domain (Davis, Petish, & Smithey, 2006; Mishra & Koehler, 2006; Supovitz, 2001).

Research across K–12 school disciplines suggests that professional development programs can improve instruction when they immerse teachers in inquiry investigations. Inquiry investigations engage teachers in activities such as comparing alternative forms of curricula and pedagogical techniques, analyzing the range of students' ideas in a targeted subject matter, connecting students' ideas to specific elements of instruction, and critiquing lesson plans in a mutually supportive teacher community (Borko, 2004; Franke, Carpenter, Levi, & Fennema, 2001; Lawless & Pellegrino, 2007; Lewis, Perry, & Murata, 2006). Research on professional development in science education echoes these findings and highlights the value of teachers' understanding of the discipline they are teaching (Garet, Porter, Desimone, Birman, & Yoon, 2001).

We examined the emerging body of research on professional development programs in K–12 technology-enhanced science education to better understand how to support teachers' use of technology interventions, in ways that significantly improve students' opportunities for inquiry learning. These research studies varied considerably in terms of the professional development activities studied, the specific technologies used, and the methodologies employed. We used a constructivist-oriented learning framework, knowledge integration, to synthesize the findings from this diverse body of work. We examined how, and to what degree, the professional development programs supported teachers to engage in the knowledge integration learning process and the impact the programs had on teachers' use of technology to enhance students' inquiry science learning experiences.

Technology-Enhanced Inquiry Instruction

Current science teaching reforms and standards documents call for teachers to engage students in scientific inquiry (American Association for the Advancement of Science, 1993; National Research Council, 1996, 2000). Research teams have designed and refined technology-enhanced materials for inquiry learning in programs such as the Learning Technologies in Urban Schools (Rivet & Krajcik, 2004), Global Learning and Observation to Benefit the Environment (Penuel & Means, 2004), and Kids as Global Scientists (Songer, 2006). Inquiry-oriented instruction has resulted in more robust student science understanding than alternative instructional approaches (Duschl, Schweingruber, &, Shouse, 2007).

New instructional technologies can support classroom inquiry by providing opportunities for students to experiment with dynamic simulations of scientific phenomena (Pallant & Tinker, 2004; Wilensky & Reisman, 2006), engage in scientific modeling (Chang, Quintana, & Krajcik, 2010), and participate in scientific experimentation activities such as collecting data and conducting analyses using probeware and scientific databases (McDonald & Songer, 2008; Metcalf & Tinker, 2004). Students' science learning gains on target science concepts are significantly greater when using these technology-enhanced innovations than when using typical textbook-based materials alone (Chang et al., 2010; Geir et al., 2008; Lee, Linn, Varma, & Liu, 2009; Quintana et al., 2004).

Integrating technology-enhanced inquiry materials in science classrooms requires professional development because the majority of science teachers have limited experience implementing instructional technologies designed to enhance students' conceptual understanding (Fishman, Marx, Blumenfeld, Krajcik, & Soloway, 2004). Among the many challenges teachers face in implementing instructional technologies, some include the navigation of a new environment or tool, the need to troubleshoot spontaneous technical difficulties, management of students' autonomous learning at different paces, and the provision of guidance for student interaction with multivariate simulations and real-time data (Songer, Lee, & Kam, 2002; Varma, Husic, & Linn, 2008). Furthermore, David, Petish and Smithey, (2006) highlighted the difficulties that even well-prepared teachers encountered when trying to facilitate student inquiry in a regular K–12 classroom. The identified challenges include eliciting and building on the range of students' ideas about the target phenomena, providing ample time and guidance for student-led investigations when teachers are pressed to teach all of the state content standards, and helping students to link pieces of evidence learned in different contexts.

Research reviews from the past two decades illuminate the gaps in our knowledge about professional development for technology-enhanced inquiry science and motivate this review. Lawless and Pellegrino (2007) conducted a review of literature from 1997 to 2005, analyzing studies of professional development programs that supported teachers to integrate technology tools into their instruction in different domains. The review identified benefits of professional development in terms of helping teachers gain technology skills such as locating lesson plans on the Internet. However, the review provided limited insight into the important pedagogical changes teachers made when integrating technology into instruction and the impacts technology-focused professional development had on teacher development and student learning specifically in science. Research suggests that the discipline necessarily shapes how teachers approach instruction (Grossman, Wineburg, & Woolworth, 2001). Davis et al., (2006) review contributed valuable insights regarding the challenges teachers face in guiding inquiry science learning, but it did not explore issues of technology integration, nor the role of professional development interventions in helping teachers to overcome these challenges. Other relevant reviews examined selected literature to identify variables at different levels in the school system that contribute significantly to the success or failure of an instructional innovation (Higgins & Spitulnik, 2008; Kim, Hannafin, & Bryan, 2007; Spillane, Reiser, & Reimer, 2002; Straub, 2009). These reviews however are not exhaustive of the empirical literature, nor do they provide in-depth analysis of the variables at play specifically in professional development. In summary, how and to what degree professional development in technology-enhanced science can improve teachers' practice and students' inquiry learning experiences remain critical and open questions.

Knowledge Integration Framework and Professional Development

Knowledge integration is a constructivist view that emphasizes building on the repertoire of ideas held by learners and helping learners to utilize evidence to incorporate new ideas into a coherent understanding (Linn & Eylon, 2011). The knowledge integration framework identifies four main processes that research has shown to jointly promote student and teacher inquiry learning: eliciting ideas, adding ideas, using evidence to distinguish among ideas, and reflecting and integrating ideas (Sisk-Hilton, 2009). The framework is based on extensive research suggesting that simply adding new ideas, without support to test and refine these ideas in a relevant context, is insufficient for changing one's knowledge of the target domain (Bransford, Brown, & Cocking, 1999).

Frameworks focused on teachers' pedagogical content knowledge, such as the technological pedagogical content knowledge framework, are consistent with the knowledge integration perspective in that both emphasize the goal of supporting teachers to integrate ideas from key knowledge domains to improve instruction (Justi & Van Driel, 2005; Mishra & Koehler, 2006; Penuel, Fishman, Yamaguchi, & Gallagher, 2007). The knowledge integration framework adds a specific delineation of constructivist learning process that we found were specific enough to map onto activities within a professional development program and general enough to categorize a wide variety of professional development programs' activities.

In the context of professional development, we view teachers as the learners in the knowledge integration process. Teachers have a repertoire of ideas about teaching with technology based on their observations, experiences, and preservice or professional development courses (Davis, 2003). The knowledge integration perspective emphasizes asking teachers to articulate these ideas, adding new ideas to teachers' repertoire in ways that make this new information accessible, enabling teachers to use multiple forms of evidence to distinguish among new instructional ideas and their existing views, and encouraging teachers to engage in an ongoing process of reflecting on and integrating new ideas to formulate a pedagogical framework that aims to most effectively enhance student inquiry science learning (Higgins & Spitulnik, 2008).

Elicit Ideas

The repertoire of ideas that teachers develop as a result of experience, observation, and instruction is central to learning a new professional practice. Teachers come to professional development programs with a set of views about the content they teach, the capabilities of their students, learning processes, pedagogical methods, curriculum materials, technology, and inquiry. Teachers' ideas about science instruction are supported by various forms of evidence including perceived success of their teaching, their own learning experiences, students' performance on standardized and classroom tests, and feedback from students about their satisfaction using particular instructional tools (Davis, 2003; Little, 2003). Effective professional development activities elicit teachers' existing ideas by asking for predictions, critiques of practices, and brainstorms of ideas. They elicit ideas about relevant science concepts and teaching practices so that these views can be inspected, analyzed, potentially contradicted, and refined (Trautmann & MaKinster, 2010; Yerrick & Johnson, 2009). The value of supporting teachers to articulate their initial ideas is apparent in numerous studies (e.g., Piaget & Inhelder, 1969; White & Gunstone, 2008).

Add Ideas

Successful professional development programs generally introduce new instances of and insights about technology-enhanced inquiry instruction as well as new disciplinary knowledge. Watching video recordings of classroom practice may effectively introduce new ideas (Brunvand & Fishman, 2007). Many programs also ask teachers to role-play a student using technology-enhanced curricula to introduce teachers to the ideas students may learn and the challenges students may encounter (Tosa & Martin, 2010). Teachers may also add ideas by collaborating with peers to discuss and refine lesson plans (Grossman et al., 2001). When supporting teachers in adding new ideas, the new information is most compelling when it is tightly linked to classroom practice and evidence of students' learning (Borko, 2004; Little, 2003). When new ideas are presented through a video or presentation, but not connected to teachers' existing knowledge and classroom experiences, the new ideas are often isolated in the teachers' minds and rapidly forgotten.

Distinguish Ideas

Even when ideas are connected to existing knowledge, teachers might add ideas to their repertoire but not use them in their classroom practice. Consistent with the knowledge integration framework, many studies show that teachers' new ideas about technology and inquiry science instruction do not straightforwardly replace their existing views about teaching and learning (Akerson, Cullen, & Hanson, 2009; Henze, van Driel, & Verloop, 2009; Spillane et al., 2002). Established practices supported by various forms of evidence may have developed over years of teaching. Changing these practices is slow and sometimes difficult. For example, in technology-enhanced science education, teachers may initially believe that students will learn on their own when working with computer-based simulations. Although this is a plausible goal, research suggests that students in a typical science classroom rarely learn from dynamic simulations without some teacher guidance to help the students identify salient features and link observations to key science ideas (Fishman, Marx, Best, & Tal, 2003; Spillane et al., 2002; Tal, Krajcik, & Blumenfeld, 2006).

The knowledge integration framework emphasizes helping teachers to distinguish among new and existing ideas by using evidence-based criteria to select the ideas that most aptly explained successful teaching practices. Technology-enhanced materials often collect continuous indicators of student progress that give teachers excellent opportunities to use evidence to distinguish their new ideas from past teaching practices, weigh alternatives, and reflect on how best to proceed. Technology-enhanced assessments, for example, can give teachers evidence of student thinking as they interact with computer-based simulations. Teachers can use this evidence to determine when students need external scaffolding to engage in inquiry processes such as question posing, data collection, and synthesizing while working with virtual experiments or simulations.

Reflect and Integrate Ideas

Teaching practices are usually well established, and hence change gradually. Effective professional development programs support teachers to use evidence to reflect on their knowledge and integrate ideas of science content, student learning, curriculum, and teaching to form a coherent instructional framework. This calls for an ongoing process of refining and reevaluating ideas.

Experts in the field of science teacher education emphasize helping teachers make links among their ideas to gain robust insights (Ball & Bass, 2000; Davis, 2003; Henze et al., 2009; Niess, 2005). Shulman (1986), for instance, refers to teachers' integrated knowledge about practice as pedagogical content knowledge. He frames the development of pedagogical content knowledge as an ongoing activity. Teachers gain coherent views in technology-enhanced science when teachers combine ideas about their students' conceptions of a particular topic with their new ideas about what students are learning when they conduct virtual experiments (Mishra & Koehler, 2006; Niess, 2005). For instance, teachers benefit from linking their prior knowledge about how students deal with orders of magnitude to new ideas about how students reason when constructing a computer-based model of the solar system (Henze et al., 2009).

In summary, the processes highlighted by the knowledge integration framework resonate with both research on and recommendations for effective professional development in inquiry science instruction. Professional development programs that elicit teachers' initial views related to teaching and learning provide opportunities for teachers to add new ideas about using technology to promote inquiry science learning, support teachers to use evidence from students' work to distinguish among new and existing ideas, and guide teachers to reflect on and integrate new ideas with their existing practices should improve both teaching practice and student learning.

Method

In this research we identified relevant studies on professional development in technology-enhanced science education. We used the knowledge integration framework to analyze how and to what degree the professional development programs supported teachers to engage in a constructivist-oriented learning processes and the degree of impact the programs had on teachers' use of technology to enhance students' inquiry learning experiences.

Identification of Studies

We searched the Education Full Text, PsycINFO, and Education Resources Information Center electronic databases for peer-reviewed articles published between the years 1985 and 2011 on professional development in technology-enhanced science education. Search keywords included *professional development*, *science*, and *technology*. In addition to the database search we requested research studies from leading researchers in the field of technology-enhanced science education, reviewed references, and incorporated empirical research with which we were familiar.

As shown in Table 1, we engaged in a multistep review process of the entire corpus of research to identify studies that met all of the following criteria:

TABLE 1
Articles reviewed: Source, unit of analysis, number reviewed, reasons for exclusion, and number included after review

Source	Unit of analysis	*n*	Primary reasons units excluded	*n* after review
ERIC, Education Full Text, PsycINFO databases	Citation	360	Science was outside K–12 science education (e.g., consumer science, social science) Participants were not in-service science teachers or K–12 students (e.g., pre-service teachers, college-age students) Article included limited or no empirical data on professional development program	
	Abstract	155	Use of technology was outside of K–12 science education (e.g., online professional development) Participants were not in-service science teachers or K–12 students Included limited or no data on professional development program (curriculum study with implications for professional development; editorial or introduction to special issue)	
	Article	94	20% included limited or no empirical data on professional development program 21% included limited or no empirical data on technology-enhanced curriculum or tools (e.g., focus on technology teachers or science/technology/society curriculum) 19% did not include multiple data sources and/or describe analysis 14% included a use of technology outside of K–12 science education (online professional development) 11% were not focused on science	22

(continued)

TABLE 1 (continued)

Source	Unit of analysis	n	Primary reasons units excluded	n after review
			10% had participants who were not in-service science teachers or K–12 students 3% were review articles 1% were not available	
Solicited from researchers in the field, or work we were familiar with	Article	25	Not published Included limited or no empirical data Did not include multiple data sources and/or describe analysis Participants were not in-service science teachers	13
Identified in references	Article	8		8
Total		393		43

- Includes use of technology in K–12 science education
- Involves practicing science teachers, not preservice teachers
- Involves use of technology for *more than* presentations, word processing, or noninteractive websites
- Includes more than one data source and an explicit description of data analysis techniques

We identified 43 unique studies that met all of these criteria. Articles included in the review are marked with an asterisk in the references section of this article.

Eight review articles bearing insight into professional development in technology-enhanced science education, as shown in Table 2, were not included in the analysis but informed the discussion of findings (Davis et al., 2006; Davis & Krajcik, 2005; Higgins & Spitulnik, 2008; Kim et al., 2007; Lawless & Pellegrino, 2007; Spillane et al., 2002; Straub, 2009; Tamin et al., 2011).

Data Analysis Procedure

We used a two-step data analysis process guided by the knowledge integration framework, as shown in Table 3, to examine how each professional development program supported participants to develop new pedagogical practices that leveraged technology to enhance students' inquiry learning experiences. First, we coded the professional development activities described in each study. We categorized each activity, within each professional development program, according to the knowledge integration process it aimed to promote: *eliciting teachers' ideas*, *supporting teachers to add new ideas*, *supporting teachers to use evidence to distinguish ideas*, or *supporting teachers to reflect and integrate ideas*. Then, we coded the professional development program as a whole (*low*, *medium*, or *high*) in terms of its overall degree of support for teachers to engage in each of these constructivist-oriented learning processes.

Next, we coded the impact of the professional development programs in terms of the degree to which the program supported teachers to integrate technology-enhanced instruction into their teaching practice to enhance students' inquiry learning experiences. By enhancing students' inquiry learning, we mean professional development supported teachers to use technology to help students construct understanding of a targeted science topic in ways that students could not do otherwise in a typical science classroom (e.g., conducting virtual experiments using dynamic simulations of difficult-to-see science phenomena; generating and testing models of complex data sets; making predictions and collecting and analyzing data using probeware and data analysis software; gathering feedback from different sources to iteratively refine work). This stands in contrast to supporting teachers to use technology to enact direct-instruction-oriented teaching practices (e.g., showing students a model) or supporting teachers to use technology to engage in an activity that is not directly linked to a learning goal (e.g., having students collect real-time data without making predictions and analyzing the data in light of them). To ensure consistency in our analysis of the impacts of professional development programs, we excluded studies from this level of analysis that did not report on teachers' use of the technology in the classroom. Also, when there was more than one study reporting on the same data set, we excluded the study with less data.

TABLE 2

Review articles, foci, literature reviewed, and relevant findings

Citation	Focus	Literature reviewed	Findings relevant to this review
Davis and Krajcik (2005)	Educative curriculum design	Selected literature on teacher knowledge, teacher learning, and curriculum design	Identifies design principles for educative science curriculum materials that will support teacher learning, in addition to student learning
Davis, Petish, and Smithey (2006)	Challenges beginning science teacher face	Exhaustive review of empirical research related to the theme of challenges new science teachers face	Identifies key challenges new science teachers face such as building on students' background experiences and ideas and combining content and pedagogical knowledge
			Suggests that supportive colleagues, engaging in reflection, and preservice coursework can help teachers to become more effective science teachers
Higgins and Spitulnik (2008)	Teaching in technology-enhanced science	Selected empirical research on teacher development in technology-enhanced inquiry science	Identifies disconnect between teachers' knowledge about technology and what it takes to implement technology in the classroom
			Suggests collaboration with other teachers contributes to teachers' use of technology
Kim, Hannafin, and Bryan (2007)	Technology-enhanced inquiry science teaching and learning	Selected theoretical literature and empirical research related to the design and implementation of technology-enhanced science curriculum	Develops a framework explicating the factors involved in integrating technology-enhanced curriculum in science classrooms

(continued)

TABLE 2 (continued)

Citation	Focus	Literature reviewed	Findings relevant to this review
Lawless and Pellegrino (2007)	Professional development in technology	Exhaustive review of empirical research on professional development to support teachers' integration of technology into instruction	Identifies benefits of professional development in terms of helping teachers gain technology skills such as locating lesson plans on the Internet
Spillane, Reiser, and Reimer (2002)	Implementation of educational reforms	Selected literature on individual sense making of new stimuli	Suggests that people adapt innovations to fit their existing beliefs and practices People require substantial experience with an innovation to understand how the innovation can substantially enhance instruction
Straub (2009)	Adoption-diffusion theories	Selected literature stemming from three different adoption-diffusion theories	Suggests that people perceive the usefulness of a technology in terms of its capacity to enhance their performance and its ease of use This perception influences individuals' adoption of technology
Tamin, Bernard, Borokhovski, Abrami, and Schmid (2011)	Impact of technology on classroom learning	Second-order meta-analysis of 37 different meta-analyses on technology and learning	Identifies a significant, positive, small to moderate effect size favoring the utilization of technology in the classroom over technology-free instruction Suggests that aspects such as instruction, pedagogy, teacher effectiveness, and fidelity of technology implementation may have a greater effect on student learning with technology than the technology itself Technology that provided support for cognition, rather than presentation of content had a significantly greater effect on student learning

To establish coding reliability, three researchers reviewed the professional development programs in each study individually and used the knowledge integration rubric shown in Table 3 to code the programs' level of support for teachers to engage in knowledge integration processes and the degree of impact the programs had on teachers' use of technology to enhance students' inquiry learning. In the initial round of coding, researchers reached an agreement level of 94%. The disagreement related to insufficient detail in the coding rubric regarding the kind of evidence needed in professional development activities to fully support teachers to distinguish among ideas. After adding further detail to the coding rubric, each researcher recoded studies individually, and researchers reached an agreement level of 100%.

Characteristics of Research Studies in Technology-Enhanced Science

Overall, we identified a total of 43 studies that were published in leading peer-reviewed journals and systematically collected and analyzed data on professional development in technology-enhanced science education. The studies collectively involved more than 2,350 teachers and 138,000 students. To control for the duration of professional development, we formed two groups: professional development programs of 1 year or less (28 studies) and professional development programs that continued for 2 years or more (15 studies).

Most studies involved secondary schoolteachers (Grades 6–12) who were experienced in terms of teaching science and novices in terms of using instructional technology. The studies investigated 11 different, specific technologies (Table 4). We differentiated between technology tools that facilitated a specific practice such as data collection and technology-enhanced curricula that scaffolded instruction using multiple inquiry practices. Studies were split almost evenly between those supporting teachers' use of technology-enhanced inquiry curricula and those supporting teachers' use of technology tools.

Short-term and long-term professional development programs varied the most in terms of their goals and outcome measures. The short-term professional development programs focused primarily on helping teachers to use a new technology in their classroom. The studies relied primarily on surveys, teacher journals, or classroom observations. Of these studies, 22% documented effects of professional development on students' inquiry science learning experiences. In comparison, the long-term professional development programs focused on helping teachers to integrate the technology into their practice to enhance students' inquiry science learning. Most of these studies included some indicator of change in teachers' pedagogical approach, and 40% of the studies included measures of student science learning outcomes.

The Role of Professional Development Design in Technology-Enhanced Inquiry Science

We considered the level of support provided by each professional development program for teachers to engage in knowledge integration learning processes in relation to the impact of the professional development program on teachers' use of technology to enhance students' inquiry science learning experiences. As shown in Table 5, when the studies were examined as a whole, they provided ample evidence

(Text continues on p. 424.)

TABLE 3

Knowledge integration (KI) coding categories and definitions

KI process	Definition	Example
Elicit ideas, make predictions	Gather teachers' initial beliefs, values, and/or knowledge about technology-enhanced science units, visualizations, and virtual experiments	Discuss prior experiences with technology-enhanced science, brainstorm obstacles, respond to questionnaires, talk with researcher
Add new ideas	Engage teachers with new ideas about using technology to facilitate student inquiry	Observe mentor or peer using technology-enhanced instruction, role-play student using the materials, read research on teaching and learning with technology, watch classroom enactment video, gather ideas from experienced peers, listen to presentation
Distinguish ideas	Enable teachers to use evidence of student learning to evaluate technology-enhanced instructional practices and materials	Compare technology-enhanced curricula and tools in terms of impacts on learning, generate rubric to assess students' learning from enactment of the technology, critique video of teaching using technology, problem-solve technology-enhanced instruction enactment issues with peers and mentor
Reflect and integrate ideas	Support teachers to integrate new ideas on technology-enhanced science with their existing views about instruction	Use student data to customize specific elements of technology-enhanced instruction, synthesize experiences in journal entries, explain new practices to peers or parents, mentor others
Professional development support for teachers to engage in KI processes	**Definition**	**Example**
Low	Professional development supported teachers to add ideas, or to distinguish ideas without using evidence	A mentor was available to help teachers use the new technologies in the classroom, but was not called on or used only to solve technical issues

(continued)

TABLE 3 (continued)

KI process	Definition	Example
Medium	Professional development supported teachers to add new ideas about technology in science, and partially supported teachers to distinguish ideas by guiding them to reflect on their implementation experiences; did not include evidence of student work	Teachers participated in requisite discussions with colleagues and/or a mentor where they were guided to share experiences using the technology to enhance inquiry learning and evaluate alternatives
High	Professional development supported teachers to add new ideas from expert guidance about technology in inquiry science, use evidence from implementation experiences and student work to distinguish effective practices, and integrate effective practices into instructional refinements that enhance inquiry	Teachers discussed the role of technology in student learning, implemented the technology-enhanced unit, analyzed evidence from student work in relation to their teaching strategies, and refined their teaching approach
Professional development impact on teachers' integration of new practices to enhance student inquiry learning	**Definition**	**Example**
Minimal	Fewer than one third of participants changed practice in direction of using technology to enhance student inquiry learning (includes increased frequency of use of technology without a focus on inquiry)	Most teachers did not use the technology in the classroom or used the technology to support a direct instruction approach such as showing a model, or grading right–wrong without providing opportunity for reflection
Partial	One third to two thirds of the participants changed some of their practice in direction of using technology to enhance inquiry learning	Some teachers with existing inquiry teaching skills used technology to monitor student learning in data collection and engage students in assessing their own learning
Full	More than two thirds of the participants changed their practices in direction of using technology to enhance student inquiry learning, or students changed beliefs about nature of science or understanding of science topics as a result of teachers' improved technology-enhanced instruction	Teachers created new ways for using technology such as supporting students to generate concept maps to plan their writing to explain a scientific phenomena, gather feedback from peers and the teacher, and revise their plan

TABLE 4
Technology tools and curriculum in reviewed studies

Technology	Goal of technology	Total number of studies
Classroom Response System (CRS)	The goal is to support instructors to customize whole class instruction to students' needs. The teacher uses a laptop or desktop to pose a question, students respond using wireless clickers, and then the software on the instructor's computer aggregates the student responses and displays them in a histogram or some other summary form.	1
Geographic Information Technologies (GIS)	Technologies are designed to capture, store, analyze, and mange data specific to a certain location.	3
Global Learning and Observation to Benefit the Environment (GLOBE)	The goal is to support students, teachers, and scientists to collaborate on inquiry-based investigations of the environment. Students use sensors, cameras, and videotape to collect data, input data into a real-time shared scientific database, receive visual images of their data analyzed, and e-mail with collaborating GLOBE schools and scientists. http://www.globe.gov/	3
Interactive White Board (IWB)	IWBs involve a computer linked to a data projector and a large, touch-sensitive, wall-mounted electronic board, which displays projected images that can be manipulated by hand. It allows direct interaction with the screen and access to previously stored information and the Internet.	1
Kids as Global Scientists (KGS)	Based on a model of global information exchange, the goal is for students to use Web resources to investigate weather science. Students from classrooms worldwide collect and share their own data, real-time images, and dialogue about real and often sensational weather events.	1
Learning Technologies in Urban Schools (LeTUS)	The goal is for students to learn complex scientific ideas by engaging in practices that include generating and working with computer based models, constructing scientific explanations, engaging in argumentation and debate, analyzing data either gathered by students or captured within complex data sets, using probe ware, and presenting ideas to peers in visual forms such as concept maps. http://www.umich.edu/~hiceweb/iqwst/index.html	7
Public Understanding of Science (Netherlands)	The goal is to make secondary Dutch science students aware of the way scientific knowledge is produced and developed. This involves designing and using models, developing theories, and designing investigations.	1

(continued)

TABLE 4 (continued)

Technology	Goal of technology	Total number of studies
River City	A game designed with a multiuser virtual environment to teach scientific inquiry and 21st-century skills to middle school students. Students access virtual environments through their avatar and interact with digital artifacts such as microscopes and pictures and computer-based agents. http://rivercity.activeworlds.com/rivercityproject/index.html	1
Sociotransformative Constructivism (sTc)	Teachers integrate science content and learning technologies to develop curriculum units that are multicultural, gender inclusive, and inquiry based. Units can incorporate varied technology tools such as probes, laptops, digital cameras, data analysis software, and concept mapping.	3
Web-based Inquiry Science Environment (WISE)	The goal is to support students to engage in inquiry learning about scientific phenomena that research suggests are difficult to teach using the textbook and/or labs. WISE is an open-source Web-based environment that embeds dynamic computer-based visualizations including interactive simulations, graphs, and models in projects that follow successful inquiry curriculum patterns. http://wise4.berkeley.edu	10
Wireless Handhelds for Improving Reflection on Learning (WHIRL)	The goal is to enhance teachers' formative assessment. The software is for handheld devices and includes applications for students to make drawings, create scientific models, and respond to short quizzes. Student work is wirelessly beamed to teachers' computer in real time. http://www.goknow.com/Products/Sketchy/	2

for the claim: Constructivist-oriented professional development can improve teachers' use of technology to enhance students' inquiry learning experiences. When the studies were divided according to the duration of the professional development program, the effect of the professional development program design was far more pronounced in programs that were sustained beyond 1 year. Programs that supported teachers for 1 year or less had little impact on teachers' effective use of technology, regardless of their level of support for teachers to engage in the knowledge integration learning processes. This is because, studies suggest, participants were often enmeshed in potentially unavoidable technical and instructional obstacles in the first year related to implementing technology in a classroom for the first time.

As a whole, the studies suggest that when professional development supported teachers to engage in each of the knowledge integration learning processes and was sustained for more than 1 year, more than two thirds of the teachers in each professional development program enhanced their students' inquiry science learning experiences. For example, teachers formulated better questioning strategies that prompted students to connect pieces of evidence gathered from different representations in the technology-enhanced materials of the target scientific phenomena (e.g., a molecular simulation of a chemical reaction, a chemical formula, and a video of an explosion; Williams, 2008). Teachers improved their feedback by monitoring their students' responses to embedded assessment or teacher-posed questions as students interacted with a simulation or conducted a virtual experiment and used this information to decide when and how to intervene (Fishman et al., 2003; Gerard, Spitulnik, & Linn, 2010; Slotta, 2004). Some teachers began to guide students in using technology to create artifacts, such as robots, models, and graphs, to visually explain their ideas to their peers (Desimone, Porter, & Garet, 2002; Lavonen, Juuti, Aksela, & Meisalo, 2006; Rodrigues, 2006; Rodriguez, Zozakiewicz, & Yerrick, 2005; Zozakiewicz & Rodriguez, 2007).

When looking at the studies of professional development programs that lasted 1 year or less, the findings suggest that teachers' use of technology in the first year is less influenced by the design of the professional development program and more heavily influenced by the technical and instructional challenges related to implementing the technologies in a typical classroom for the first time. As shown in Table 5, three studies documented 1-year professional development programs that supported teachers to engage in all of the knowledge integration learning processes but had very limited effects on the participating teachers' practices or students' science learning (Guzey & Roehrig, 2009; Penuel & Yarnall, 2005; Yarnall, Shechtman, & Penuel, 2006). After participating in comprehensive, constructivist-oriented professional development, fewer than two thirds of the participating teachers in each of these studies used the technologies to enhance their students' inquiry science learning experiences. Rather, the majority of the participating teachers in each of these studies adapted the technology to support a direct instruction approach to teaching. By a direct instruction approach, we mean that a majority of teachers used the technology tool or curriculum to show or demonstrate science content to students rather than engage students in an inquiry investigation (Guzey & Roehrig, 2009; Penuel & Yarnall, 2005; Yarnall, Shechtman, & Penuel, 2006).

Studies documented similar, substantial, and unanticipated technical and instructional challenges faced by teachers and researchers when implementing technology in a typical school classroom in the first year. These challenges can likely explain the mixed results of the 1 year or less professional development programs. Unexpected technical issues arose related to Internet connectivity, the setup of specialized equipment, outdated school software and hardware, Internet security and privacy blocks, and unknown technical bugs. As one participating teacher remarked,

> The [GIS] map worked fine at home, but the layers [on the map] were unavailable once it was loaded onto a school computer. . . . [T]he technology coordinator worked to resolve the issue and thought at one point that he had, but the map failed once more, so in the interest of time I moved to plan B which involved a little Google Earth tour of the area. This worked so long as I controlled a single computer and used an LCD projector to share with the students. Moments after I allowed the kids to work on individual machines, the network overloaded and effectively shut down. (Trautmann & MaKinster, 2010, p. 359-360)

Comments like this were frequent from teachers as they used a new technology in their classroom in the first year (Blumenfeld, Fishman, Krajcik, & Marx, 2000; Gerard, Spitulnik, et al., 2010; Kershner, Mercer, Warwick, & Staarman, 2010; Ketelhut & Schifter, 2011; Rodriguez, Zozakiewicz, & Yerrick, 2005; Songer et al., 2002; Trautmann & MaKinster, 2010; Varma et al., 2008). When the professional development was sustained beyond the first year, teachers and researchers were able to overcome most of these technical issues. Researchers improved the functionality and ease of use of the technology and, in some cases, developed teacher and schoolwide capacity to address spontaneous technical challenges (Fogleman, Fishman, & Krajcik, 2006; Gerard, Bowyer, & Linn, 2010; Lavonen et al., 2006; Rodrigues, 2006; Trautmann & MaKinster, 2010; Wilder, Brinkerhoff, & Higgins, 2003).

In addition to technical challenges, the well-established nature of teachers' instructional practices presented greater challenges to researchers than they had anticipated in the first year of the professional development program. A majority of teachers across the studies deprioritized the use of the technology-enhanced materials in light of other school demands, competition from other available curricular resources particularly in schools with low average yearly progress scores, and a lack of administrative support (Blumenfeld et al., 2000; Penuel & Means, 2004; Rodriguez et al., 2005). Furthermore, researchers observed in first-year classroom observations that most teachers rarely if at all integrated knowledge of students' conceptions and abilities with their technology-enhanced instructional strategies (Penuel, Boscardin, Masyn, & Crawford, 2006; Schneider, Krajcik, & Blumenfeld, 2005; van Driel & Verloop, 2002; Williams, Linn, Ammon, & Gearhart, 2004). Teachers were challenged in the first year to transition students between computer-based work and offline activities (Fishman et al., 2003; McNeil & Krajcik, 2008), monitor student progress (Gerard, Spitulnik, et al., 2010; Penuel & Yarnall, 2005), and pace a classroom of students engaged in autonomous investigations (Guzey & Roehrig, 2009; Slotta, 2004; Varma et al., 2008).

In addition, a majority of teachers were challenged to integrate technology-enhanced instruction with science learning goals and/or existing curriculum in the first year. Most teachers used the technology to replicate what they were already doing (Kershner et al., 2010; Penuel & Yarnall, 2005; Rodrigues, 2006), or teachers were challenged to integrate the technologies into their instruction or used the technology to teach standards not aligned with the technology activities (Rodriguez et al., 2005; Ruebush et al., 2010), or some teachers did not use the technology at all because they did not think it helped them to address learning goals (Blumenfeld et al., 2000; Penuel et al., 2007; Penuel, Fishman, Gallagher, Korbak, & Lopez-Prado, 2008; Penuel & Means, 2004).

It is notable that in three studies, the short-term professional development programs supported teachers to engage in all of the knowledge integration learning processes, and more than two thirds of the participating teachers successfully used the technology to significantly improve their students' inquiry science learning experiences (Tan & Towndrow, 2009; Trautmann & MaKinster, 2010; Yerrick & Johnson, 2009). In these three studies, the participating teachers had extensive time to cultivate new teaching practices, test these practices in their classroom, examine outcomes with colleagues and researchers, and refine their practices and try again. Teachers participated in a minimum of a 2-week institute during the summer, and during the school year teachers participated in monthly workshops with other participating teachers and the researchers and in weekly meetings with the researchers.

Summary of Findings

Tamin et al. (2011) suggested that the capacity of technology to improve student learning depends more on teacher pedagogy, content knowledge, and instructional goals than the design of the technology itself. Our review of the literature is consistent with this view. If the teachers, in the programs reviewed, were engaged in comprehensive, constructivist-oriented professional development programs that were sustained for more than 1 year, a majority of the participating teachers were likely to use the technological tool or curriculum in powerful ways to significantly improve their students' inquiry science learning experiences. Alternatively, if teachers were provided with partial professional development that supported them to add ideas but not to gather data to distinguish among their new and existing views, or if teachers were not supported long enough to overcome common, first-year technical and instructional obstacles, teachers were likely to use the technology in ways that added little value, if any, to students' inquiry science learning.

Unpacking the Benefits of the Professional Development Design: Case Studies

Our analysis suggests that the degree to which the professional development programs supported teachers to engage in a constructivist-oriented learning process significantly influenced the participating teachers' use of the technology to enhance students' inquiry learning experiences. To provide a more nuanced account of the benefits of supporting teachers to engage in all four of the knowledge integration processes, we discuss three professional development programs in depth. We show how elements of the knowledge integration framework differentiated the professional development programs and identify characteristics of professional development activities that effectively supported teachers in making predictions, adding new ideas about technology-enhanced instruction, distinguishing effective practices to support inquiry learning, and continuously integrating improved teaching strategies.

TABLE 5
Duration of professional development, professional development support for learning processes, and impacts on teachers' use of the technology to enhance inquiry

Duration of PD	Professional development support for knowledge integration learning processes	*n* (studies; *N* = 32)[a]	Impacts of professional development on teachers' use of the technology to enhance inquiry learning		
			Fewer than one third of teachers changed practices to enhance inquiry learning	One third to two thirds of teachers changed practices to enhance inquiry learning and/or students reported value for technology	More than two thirds of teachers changed practices to enhance inquiry learning and/or students improved learning gains
1 year or less	Low	4	4	0	0
	Med	11	4	6	1
	High	5	1	1	3
	Total	20	9	7	4
2+ years**	Low	3	3	0	0
	Med	3	1	0	2
	High	6	0	0	6
	Total	12	4	0	8
All studies in analysis***	Low	7	7	0	0
	Med	14	5	6	3
	High	11	1	1	10
	Total	32	13	7	13

a. Excluded studies that did not report on the implementation of the technology in the classroom or school. For example, a study that reported on change in teachers' knowledge was not included in this analysis. When more than one study reported on the same data set, the study with the most comprehensive data on professional development was included and the other excluded in this analysis.
** Fisher's exact test, $p = .01$. ***Fisher's exact test, $p = .00$.

We use three cases of professional development programs to illustrate the range of support, documented across studies, for teachers to engage in knowledge integration processes (see Table 6). The three cases were selected based on the number of peer-reviewed studies available characterizing their activities and outcomes and on the representative nature of the activities used in the programs to support knowledge integration processes. As evidenced in these cases, we found that the professional development programs varied most significantly and importantly in their support for teachers in *distinguishing* and *integrating* ideas. The nature of the technology innovation, opportunities for teachers to link evidence of student learning to discrete elements of technology-enhanced instruction, and collegial collaboration also contributed to success. We describe the professional development activities that supported teachers to engage in the knowledge integration processes and the influence of the activities on teachers' use of technology to enhance students' inquiry science learning.

Global Learning and Observation to Benefit the Environment (GLOBE), Sociotransformative Constructivism (sTc), and Learning Technologies in Urban Schools (LeTUS) professional development programs involved a range of technology foci from tools such as probes and data analysis software to 8-week technology-enhanced curriculum units. Each of the professional development programs continued for more than 1 year and worked with all of the science teachers in a school or district. University researchers led the professional development in all three programs. In GLOBE and LeTUS, school districts also facilitated some of the professional development as the programs scaled up to support larger numbers of schools and teachers.

Eliciting ideas. All three programs supported teachers in similar ways in *eliciting* ideas. The programs elicited teachers' ideas about using technology in the science classroom through individual meetings with teachers and group discussions during summer institutes. Researchers also gathered teachers' views on how to design the summer institutes.

Adding ideas. All programs involved teachers in a 1- to 2-week summer institute to design learning activities, use the technologies like a student, experience models of teaching practices, and work side-by-side with education, science, and technology experts. In sTc and LeTUS, extensive follow-up support was also provided to help teachers add ideas about using the technology in their classrooms. The sTc and LeTUS university mentors helped teachers set up the technology equipment, modeled instructional practices in the classroom, and met with teachers in monthly meetings to reflect on implementation.

GLOBE provided less individualized support, consistent with the high number of teachers participating in the program. GLOBE made available to teachers as needed instructional mentors, technology specialists, and a website. The website included extensive documents detailing activities to do with GLOBE technology tools and the alignment of those activities with specific state science standards.

Distinguishing and integrating ideas. The programs diverged considerably in terms of their activities to support teachers in distinguishing and integrating ideas. More specifically, programs differed in the degree to which they supported teachers in reflecting on evidence of student learning to sort out their views. Teachers' access to relevant evidence depended on the programs' availability of assessments aligned with the technology-enhanced tool or curriculum and the availability of time for teachers to reflect on the data in relation to their teaching strategies.

TABLE 6
Professional development (PD) cases

Technology	GLOBE	sTc	LeTUS
Number of articles	3	3	7
PD support for teachers to engage in knowledge integration learning processes	Low	Med	High
Duration of PD studies (years)	2	1.25	2+
PD facilitator	Regional partners	University professors	University professors, then district
Participants	Schools and teachers volunteered, $N = 900+$	All science teachers in 1 school, $N = 11$	District selected schools, $N =$ about 40
Eliciting ideas	Brainstorm with teachers; survey	Interview of teachers	Brainstorm with teachers
Adding ideas	Summer institute	Summer institute, monthly meetings, and mentor visits to classrooms	Summer institute, monthly meetings, mentor visits to classrooms
	Mentor available		
	Lessons and standards-alignment documents on website		
Distinguishing and integrating ideas	Mentor available	Mentor prompted teacher reflection on practice during teaching	Teachers examined student pre–post assessment data to distinguish learning difficulties and elements of instruction needing improvement
	Opportunity to collaborate with other schools		
	Examining examples from prior success		

(continued)

TABLE 6 (continued)

Technology	GLOBE	sTc	LeTUS
Outcomes: Frequency of use	Limited use after first year More use when have PD mentoring and incentives, and collaboration with other schools	Limited use in first year	Limited use in first year
Outcomes: Teacher learning	Teachers who reported using GLOBE to support inquiry collaborated with other GLOBE schools	Substantial teacher knowledge growth and confidence using technology	In subsequent years some teachers used strategies generated in PD including better transitions between activities, quick formative assessments, more links to offline activities
Outcomes: Student understanding	Nothing reported	Students reported the value of working with technology in comparison to traditional methods	Several studies showed student pre–post test gains as a result of participation in PD; outcomes decreased when PD facilitation transferred to the school district
Obstacles	Technology access Integrating GLOBE with curriculum Competition with other school demands Competition with other curricular resources Teachers not accessing mentor support	Technology access Integrating sTc with curriculum Competition with other school demands	Technology access Competition with other school demands Limited school leadership

GLOBE provided minimal individualized support for teachers to distinguish and integrate ideas. Rather, the program made resources available and depended on teachers to access these resources and relate them to their practice. The resources included a local mentor who would visit the classroom if called on, contact information for a network of participating GLOBE schools, and documentation of previously successful GLOBE lessons and their alignment with specific state science curriculum standards. Each of these supports was intended to help teachers distinguish GLOBE activities that would be most useful for their particular class and to integrate the activities so that they connected to their existing instructional program. Because GLOBE developers intended teachers to develop activities incorporating GLOBE tools into their own curriculum, there were no predetermined GLOBE measures of student science learning.

sTc, like GLOBE, supported teachers to develop activities incorporating varied technology tools and integrate these activities into their existing curriculum. This meant that teachers used different technology tools in a variety of ways and lacked a common measure of student science understanding. sTc, unlike GLOBE however, worked with a small number of teachers and was hence able to provide ongoing, individualized support for teachers to distinguish and integrate ideas. sTc provided a mentor in the classroom to help teachers implement each new technology-enhanced activity and to prompt teachers' reflection on the activity's success in terms of making their instruction more inquiry oriented, culturally relevant, and gender inclusive. sTc also held monthly meetings for teachers to share their technology-enhanced instructional experiences, exchange technology-enhanced lesson plans with colleagues, and collaboratively problem solve implementation challenges. The meetings did not provide time for teachers to develop criteria for evaluating students' work.

LeTUS provided substantial support for teachers to reflect on evidence of student learning in relation to the technology-enhanced activities, distinguish student ideas and effective strategies, and integrate new teaching approaches into their repertoire. LeTUS provided teachers with both access to detailed information on student learning with technology-enhanced curriculum and time for teachers to test and refine their ideas.

The LeTUS professional development program supported teachers in evidence-based instructional customization. After participating in a summer institute, teachers implemented a technology-enhanced curriculum unit in their classroom. During the 8-week project enactment, the researchers met weekly with the teachers to discuss progress, problem solve implementation challenges, examine student work in relation to elements of instruction, and generate strategies to improve the curriculum and teaching strategies. For example, Fishman et al. (2003) documented teacher participation for 2 consecutive years in a LeTUS professional development program focused on an 8-week technology-enhanced water quality unit. In the first year, teachers enacted the unit with some support from the researcher. Teachers and researchers then examined the pre–post student assessment data and found that students had difficulty on constructed response items about watersheds. Teachers generated a list of potential problems with their instruction on watersheds that may have limited student understanding. This discussion led to generation and practice of new teaching strategies to improve student understanding of watersheds, such as supporting students to build models that explicitly link topographical features and water flow. Teachers tested these new ideas in the upcoming year when enacting the water quality unit for a second time.

Outcomes and knowledge integration framework. All of the programs supported eliciting and adding ideas. In each program, some of the participating teachers reported gaining new knowledge about technology tools to support inquiry learning. The programs differed in supporting teachers in distinguishing and integrating ideas and in sustaining the process of using student work to reflect and refine practice. GLOBE was rated low, sTc medium, and LeTUS high in support for teachers to engage in each of the constructivist-oriented learning processes. These differences affected program outcomes.

The programs varied in the degree to which teachers integrated the technologies to enhance students' inquiry learning experiences. Teachers in GLOBE reported significant difficulty integrating the technology tools with their existing curriculum, consistent with the low level of support for teachers to engage in knowledge integration processes. As a result, most GLOBE teachers did not use the technology tools in their classrooms in spite of their participation in summer institutes and the available classroom support. Of the teachers who did use GLOBE tools, some implemented them in ways that were inconsistent with the designer's intentions. These teachers reported using the GLOBE technology tools to teach science standards that were not aligned with the GLOBE lessons.

Although most teachers did not use GLOBE tools, some did report feeling prepared to use the GLOBE tools to support inquiry. Those feeling more prepared reported they had opportunities to distinguish and integrate ideas by (a) collaborating with teachers and students in another school to share data and analyses, (b) receiving professional development from a university-based provider that focused activities on linking students' scientific inquiry to GLOBE experiments, and/or (c) receiving extensive professional development focused on relating GLOBE lessons to their curriculum.

In sTc, researchers reported that teachers used the technology tools when the researchers were in the classrooms to provide support. But when teachers were expected to lead a technology-enhanced lesson independently, they reported difficulty in integrating the technologies with science content, consistent with the medium level of support for teachers to engage in the knowledge integration processes. For example, one teacher in sTc used Vernier probes during the fall semester, with researcher support, as a part of a unit on ecology. In spring, the teacher invited the researchers to her classroom to help implement a unit on electricity that incorporated voltage probes and data analysis software. When the researchers suggested the teacher lead the electricity activity on her own while the researchers observed, the teacher reported that she had not prepared for the activity and did not know enough about electricity to link the use of probes to science learning goals. Researchers reported similar instances in all of the teachers' classrooms during the first year. The researchers responded by modifying their professional development approach. They prompted teachers to better prepare for the lessons and modeled how to teach the lesson in the classroom. However, at the start of Year 2, researchers reported that they continued to be concerned about the differing levels of teacher participation.

LeTUS researchers found that most teachers changed their technology-enhanced teaching practices to improve students' understanding of watersheds, consistent with the high level of support for teachers to engage in the knowledge integration processes. The videotaped classroom observations from Fishman et al. (2003) suggested that, in the second year, teachers employed several of the teaching strategies generated in the professional development workshop. For example, teachers facilitated "bell work" (quick problems for students to complete immediately after the bell rings to start class) where maps of watersheds were depicted with questions that required students to link topographical and hydrological features in their answers. As a result of the change in teachers' practices from Year 1 to Year 2, student pre–post gains on the selected watershed items also increased significantly. Rivet and Krajcik (2004) reported that student learning gains significantly improved from Year 1 to Year 3 as a result of the technology-enhanced inquiry curriculum and professional development.

Surprisingly, in the LeTUS program, student performance *decreased* in Year 4 relative to the initial levels of Year 1 when the school district assumed leadership for the professional development. This finding is consistent with Geir et al. (2008). Both attributed the decrease in student learning gains to the transfer of professional development leadership in Year 4 from the university curriculum developers and researchers to the school district administration. The district programs offered less individualized support for teachers. District-run programs could have also changed the focus of the professional development workshops from inquiry instruction to direct instruction. This change echoes the findings of Penuel et al. (2007) who reported that GLOBE professional development activities organized by school-based partners were less focused on student inquiry and more focused on data collection protocols than were professional development activities organized by GLOBE university partners.

In summary, the level of support provided for teachers to engage in each of the knowledge integration processes in the professional development program influenced teachers' use of the technology to enhance students' inquiry learning experiences. The differentiating factors among the programs were primarily their support for teachers to distinguish ideas and engage in sustained reflection and refinement of practice. Interestingly, when the support for teachers' use of the technology intervention diminished, the effect of the materials on student learning also diminished. This suggests that a 2-year program of support may not be sufficient to enable teachers to continue using the materials on their own to enhance students' inquiry learning. This is not particularly surprising since the school contexts studied were not necessarily supportive of inquiry-oriented instruction.

Obstacles. In the GLOBE, sTc, and LeTUS programs, the participating teachers and the researchers were surprised by the challenges they faced in the first year related to integrating technology into science instruction. It required extra time for teachers to set up technology equipment; it was difficult for teachers to secure access to enough computers for a long enough time to complete an inquiry unit; it was challenging for teachers to plan a technology-enhanced lesson that addressed science standards; and it was difficult to get support from school leadership, colleagues, and parents for teachers to diverge from using the textbook alone. In addition, teachers faced immense pressure to cover all of the science standards in the school year, which meant there was little time to engage students in extended inquiry investigations. Furthermore, teachers' reported that the time needed to learn to use the technology tool or curriculum was often in competition with the time they needed to commit to other, more immediate school demands, such as grading, meeting with parents, and addressing student discipline issues. Teachers also reported, in some cases, that they did not use the technology-enhanced materials because they had other, easier-to-use and potentially more effective, curricular resources available.

This lengthy list of difficulties encountered in the first year prevented the majority of teachers in each program from using the technology interventions to enhance students' inquiry learning experiences. In spite of teachers' stated desire to use the technology tool or curriculum and their participation in a 1- to 2-week summer institute, GLOBE, sTc, and LeTUS researchers found that few teachers in the first year actually implemented the technology-enhanced materials in their classroom. Teachers' commitment to technology-enhanced instructional reform and their use of the materials increased with each year of participation in all three programs. Factors that appeared to help teachers overcome the first-year obstacles included collaborating with other schools and teachers and receiving professional development from a university-based partner rather than a school district partner.

Features of the Professional Development Design That Supported Knowledge Integration

The cases illustrated the professional development features across studies that supported teachers to add, distinguish, and integrate new practices using technology to enhance students' inquiry learning experiences. The key features included curriculum customization rather than curriculum design, time to test and refine instruction, and sustained collaboration with a mentor, colleagues, and university-based professional development facilitators. We review the evidence for these features across the programs reviewed.

Curriculum customization versus curriculum design. The studies suggest teachers needed support to distinguish effective ways to use new technologies, especially when the goal was to support inquiry learning. The majority of professional development programs introduced new technology tools and expected teachers to design their own lessons incorporating the technologies into their curriculum to enhance students' inquiry learning. Teachers were encouraged to design a lesson on a topic of their choice. This professional development approach had limited success. Teachers lacked the necessary expertise to design inquiry-oriented materials and to distinguish the most valuable uses for the technology to enhance inquiry learning. Teachers also lacked the time to refine the lessons based on evidence of student learning. These challenges are not surprising. Professional designers typically conduct numerous trials before identifying effective uses for technologies to support inquiry learning (Design-Based Research Collective, 2003).

The technology tools introduced in the professional development programs were designed to support classroom assessment (Classroom Response System, Wireless Handhelds for Improving Reflection on Learning), data collection

(GLOBE, Geographic Information Technologies), and communication (word processing, presentation software). In some of the tool-focused programs, an expert mentor guided the teachers to design inquiry-oriented lessons that incorporated the technology tools. In most of these programs, the mentor also visited the classroom to model enactment strategies and help teachers to navigate the spontaneous technical challenges (Guzey & Roehrig, 2009; Rodriguez et al., 2005; Valanides & Angeli, 2010). In the other tool-focused programs, teachers utilized the information presented in a professional development workshop to design a technology-enhanced lesson on their own or with their colleagues (Cantrell & Knudson, 2006; Kershner et al., 2010; Meichtry & Smith, 2007; Penuel et al., 2008; Penuel & Yarnall, 2005; Ruebush et al., 2010; Yarnall et al., 2006).

In most of the tool-focused professional development programs, teachers added new ideas about possible uses for the technology tools but did not distinguish effective ways to integrate the tools into their existing instruction to enhance students' inquiry learning. For example, a long-term study by Desimone et al. (2002) evaluated the government-funded Eisenhower professional development programs. The programs aimed to support thousands of teachers in incorporating technology tools into science instruction to improve student learning. Desimone et al. found that the professional development positively increased science teacher use of technology after 3 years, but teachers most frequently used the technology to support word processing to help students write reports rather than using the technology to support more powerful and potentially transformative learning experiences.

In contrast to technology tools, the technology-enhanced science curricula introduced in the professional development programs provided scaffolding or guidance for students to engage in inquiry (Quintana et al., 2004). Curricula such as LeTUS, Kids as Global Scientists (KGS), River City (Ketelhut & Schifter, 2011), and the Web-based Inquiry Science Environment (WISE) embedded innovative technologies including interactive simulations, motion probes, and modeling software in 1- to 8-week inquiry-oriented projects that guided students' investigation of a scientific phenomenon. These curricula demonstrated a significantly positive effect on student science learning in classroom testing prior to their incorporation in the professional development program (e.g., Geir et al., 2008; Lee et al., 2009; Songer et al., 2002).

The professional development programs focused on curriculum involved the teachers in customizing existing technology-enhanced science units. Working with existing curriculum, which already incorporated technologies into inquiry-oriented instructional activities, allowed the teachers to focus their efforts on distinguishing effective pedagogical practices to address their students' particular learning needs. For example, teachers in several long-term professional development studies refined the questions they asked students while students progressed through a technology-enhanced curriculum unit. Teachers also made more explicit links between what students were learning in the technology-enhanced unit and what students were learning in their textbook and related lab activities (e.g., Fishman et al., 2003; Gerard, Spitulnik, et al., 2010; Slotta, 2004; Williams, 2008; Williams et al., 2004).

Further support for engaging teachers in curriculum customization comes from an instructional comparison study (Penuel & Gallagher, 2009). Researchers compared lesson plans generated by teachers in different professional development programs. One program involved teachers in designing lessons that incorporated technology-enhanced visualizations using a variety of curricular resources (e.g., websites, material from conferences, their own or colleagues' lesson plans, textbooks), and the other program involved teachers in customizing lessons from an existing inquiry-oriented technology-enhanced curriculum. Researchers found that the customized lessons were of a higher quality than were teacher-designed lessons in terms of supporting inquiry and promoting student science understanding.

In summary, engaging teachers in customizing technology-enhanced curriculum materials rather than in designing instruction with new technology tools allowed teachers to build on a tested curriculum unit and use evidence of student learning to improve their teaching practices. This finding resonates with the knowledge integration process of distinguishing ideas. When teachers customized instruction, they examined the materials and developed criteria for distinguishing the new technology-enhanced instructional approach from their current practices and identified the most effective ways to leverage the technology to enhance students' inquiry science learning. In contrast, when asked to design an activity using a new technology, teachers built on what they already knew and tried to adapt the new tools to support activities they already performed such as helping students to write essays.

Time for reflection and refinement. Successful programs supported teachers in distinguishing among new and existing views by gathering evidence of student learning and examining this evidence in relation to specific elements of instruction (Fishman et al., 2003; Gerard, Spitulnik, et al., 2010; Rodrigues, 2006; Rodriguez & Zozakiewicz, 2010; Slotta, 2004; Tan & Towndrow, 2009; Trautmann & MaKinster, 2010; Wilder et al., 2003; Williams et al., 2004; Yerrick & Johnson, 2009). As seen in the LeTUS case, teachers implemented a technology-enhanced project in their classroom and gathered evidence of student learning. In multiday workshops, the teachers and researchers collaborated to reflect on the relationship among student learning, teaching strategies, and instructional decisions. Based on their analysis of students' work and their group discussions, the teachers made refinements to the technology-enhanced curriculum projects and to their teaching strategies for the upcoming classroom implementation. Evidence-based customization required technology-enhanced curriculum and assessments aligned with specific science learning goals so that the evidence gathered was germane to the customization task. It also required time for teachers to be able to test and refine aspects of their pedagogical content knowledge in the targeted technology-enhanced science topic. Assessments in these studies included pretests and posttests, embedded assessments such as scientific explanations, and student-generated artifacts. The assessments were also used to document changes in student understanding from one year to the next.

In summary, supporting teachers to distinguish ideas and to reflect and integrate ideas required time for teachers to test and refine discrete elements of their technology-enhanced instructional practice in relation to specific science learning goals. The studies lasting 2 or more years showed that the multiple iterations of curriculum implementation and evidence-based reflection allowed teachers to strengthen their pedagogical content knowledge in the context of a specific technology-enhanced unit. Teachers progressed in stages: They learned to use the technologies for the target unit, integrated the technology-enhanced unit with their existing curriculum, and customized their practices to address their particular student needs.

Mentoring and collaboration. The professional development programs studied supported mentoring and collaboration by (a) providing school-based teacher mentors and university researcher and curriculum developer mentors in classrooms, (b) involving multiple teachers from within each school, and (c) employing university-based professional developer facilitators. Each of these approaches was successful in helping teachers to articulate their own practices and add new ideas. Support for teachers to distinguish ideas and reflect on practice depended on the expertise of the mentor or collaborator and the time allocated for teachers to work with the mentor or collaborator in the professional development program (Cleland, Wetzel, Buss, & Rillero, 1999; Ketelhut & Schifter, 2011; Penuel et al., 2008; Penuel & Yarnall, 2005; Zozakiewicz, & Rodriguez (2007); Songer et al., 2002; Williams, 2008).

Mentors supported teachers in adding new ideas as they used the technology in their classroom for the first time by modeling classroom use of the technology to support inquiry (Varma et al., 2008; Yarnall et al., 2006; Zozakiewicz & Rodriguez, 2007). Mentors also helped teachers set up the equipment and navigate technical difficulties. For mentors to help teachers distinguish and integrate ideas, the studies suggest that time must be set aside for the teacher to work with the mentor to reflect on student work. When this time was not provided, the teacher called on the mentor only for technical assistance and not to think about the impact of the technology-enhanced practices on students' science understanding (Rodriguez et al., 2005; Varma et al., 2008; Yarnall et al., 2006). Furthermore, in some cases, teachers used the technology only when the mentor was present (Rodriguez et al., 2005; Zozakiewicz & Rodriguez, 2007).

Working with multiple teachers from the same school played a powerful role, studies suggest, in supporting teachers to add, distinguish, and integrate ideas in technology-enhanced science instruction (Cleland et al., 1999; Gerard, Bowyer, & Linn, 2007; Gerard, Bowyer, et al., 2010; Penuel et al., 2008; Penuel & Yarnall, 2005; Rodruiguez & Zozakiewicz, 2007; Songer et al., 2002; Williams, 2008). Collegial collaboration had a positive effect on teachers' frequency of technology use, the degree to which teachers felt prepared to support inquiry with technology, and teachers' use of technology to improve student science understanding. In two studies, teachers' collegial collaboration related directly to significant improvements in their students' science understanding (Lee et al., 2009; Songer et al., 2002). We hypothesize that collaborating teachers helped each other by providing spontaneous and immediate opportunities to reflect on teaching practices and student learning.

University-based professional development facilitators appeared to provide stronger support for teacher professional development in technology-enhanced science education than school-based professional development leaders (Geir et al., 2008; Ketelhut & Schifter, 2011; Penuel et al., 2007; Rivet & Krajcik, 2004). It appears that university-based facilitators enhanced professional development programs by supporting systematic technology use, student assessment, and customization of instruction. The studies provided some evidence that school-based mentors had difficulty sustaining the process of instructional customization and refinement and may have been less able than university-based mentors in negotiating the importance of inquiry learning with the pressure to teach all topics addressed on the state science exam.

Conclusion

Professional development in technology-enhanced science education has become a national need (U.S. Department of Education, 2009). Because of the ubiquity and relevance of technology in science, the National Science Teachers Association, the National Standards for Teacher Accreditation (National Council for the Accreditation of Teacher Education, 2008), and the U.S. federal government (U.S. Department of Education, 2009) require that schools devote time and resources to meaningful teacher preparation and professional development in technology-enhanced science education. Our understanding of what constitutes quality professional development is limited by the disparate research designs and findings among the studies in this growing body of work (Fishman et al., 2004; Lawless & Pellegrino, 2007). In this study, we used the knowledge integration framework to bring coherence to the 43 empirical, peer-reviewed research studies.

We found that professional development programs that support teachers to engage in a comprehensive, constructivist-oriented learning process can improve students' inquiry science learning experiences. The knowledge integration framework differentiated the professional development programs based on their support for teachers to engage in constructivist-oriented learning processes. When professional development programs guided teachers in eliciting, adding, distinguishing, and reflecting and integrating ideas, a majority of teachers in the program enhanced their support for students' inquiry science learning. We found that most professional development programs supported participants in eliciting and adding new ideas, but few adequately supported teachers in distinguishing ideas and in reflecting and integrating ideas.

To support the process of reflecting and integrating ideas, successful programs supported teachers in a series of instructional customizations, classroom tests, and refinements. These activities required professional development programs of sufficient duration so that teachers had time to repeatedly test their new strategies in the classroom. They also required professional guidance to help teachers generate instructional customizations that enhanced students' inquiry learning experiences rather than support a direct instruction approach.

Support for Distinguishing and Integrating Ideas

The knowledge integration framework suggests that teachers need criteria to evaluate inquiry learning and relevant evidence to sort out their ideas. This is particularly important to help teachers distinguish between well-established teaching practices and new technology-enhanced inquiry methods. In professional development, this means teachers need access to detailed documentation of students' ideas and evidence of students' progress in developing understanding of the target topic using the technology-enhanced materials. The majority of programs that focused on technology-enhanced tools provided insufficient support for teachers to reflect on evidence of student learning or to generate criteria for effective inquiry-oriented instruction. The tool-focused professional development programs studied, for the most part, did not link the tool directly to a science standard or learning goal and did not include assessments of student learning with the tool. Instead, the tool-focused professional development programs encouraged teachers to design lessons that took advantage of the technology tools to enhance their instruction, on a topic of their choosing. Teachers found integrating the technology with their existing instruction challenging and problematic. The teachers lacked the expertise to distinguish what constitutes good technology-enhanced instruction from potentially unproductive uses of technology. As a result, the majority of tool-focused studies resulted in limited teacher use of materials or teacher use of the technology-enhanced materials to enrich their existing practices, which in most cases was direct instruction. For instance, teachers substituted technology tools for existing practices, such as substituting word processing for writing and substituting computer demonstrations for lab demonstrations.

This finding underscores the importance of designing uses for new technologies rather than assuming teachers have the time and expertise to design innovative applications of these tools on their own. Smart Boards, laptops, and probeware seem to be the most common purchases when schools aim to "integrate technology" in learning. The assumption is that with professional development on how to use these tools, teachers will develop effective ways to employ the tool to enhance students' inquiry science learning experiences. Numerous start-ups funded with venture capital have this exact goal. Our review of the literature suggests that programs like these are unlikely to succeed.

For technology tools to be effectively utilized, our review suggests that the professional development must be long term, be individualized, and involve evidence-based instructional refinement. The successful programs that focused on technology tools supported teachers for multiple years in developing technology-enhanced activities (Rodrigues, 2006; Trautmann & MaKinster, 2010; Wilder et al., 2003; Yerrick & Johnson, 2009). Researchers worked with small groups of teachers to incorporate technology tools into their curriculum, test the effectiveness of their approach, reflect on the student work with colleagues, refine their technology-enhanced approach, and try again.

Professional development programs, our review suggests, are more likely to succeed if they support teachers in using curriculum units that have embedded technologies into tested inquiry-oriented activities focused on distinct science concepts. These materials, (e.g., KGS, LeTUS, River City, WISE) leveraged the technology to support student inquiry, rather than relying on the teacher to determine the technology affordances in the specified domain. The curricula also included assessments of student science learning aligned with the instructional goals to help the teachers learn from practice. In professional development studies focused on technology-enhanced curriculum, teachers examined student reasoning in relation to instruction, identified specific areas of student difficulty, reflected on potential problems in their instruction, and generated refined strategies to enhance student understanding.

By reflecting on evidence of student work and modifying their instruction accordingly, teachers cultivated new strategies that leveraged the affordances of the technologies to engage students in scientific inquiry. Teachers developed strategies to engage students in using the technology-enhanced materials to generate artifacts articulating their scientific understanding. Students generated models, robots, diagrams, and science narratives. Teachers monitored student progress on embedded assessments and used this information to customize their feedback to specific learning needs. Teachers relied on the technology to guide students' scientific investigations during class time, while they circled the room to check for student understanding or to formulate questions prompting students to link ideas learned from different sources of evidence. Each of these strategies gives us a window into the possible pedagogical content knowledge needed to optimize the use of technology in science education. Teachers' enhanced support for inquiry benefited their students' science learning. In six studies focused on technology-enhanced curriculum and evidence-based customization, student pretest–posttest gains improved significantly from one year to the next.

Going Beyond the First 2 Years

Unavoidable obstacles particular to technology-enhanced instructional reform emerged in the majority of professional development programs in the first year, as researchers and teachers implemented the technologies in the classroom for the first time. Subsequently, in the first year, few teachers in any of the programs actually used the technology-enhanced materials in their classrooms to support inquiry, in spite of teachers' participation in a 1- to 2-week workshop. Some researchers expressed surprise at this slow progress, yet the obstacles were similar across programs. Technical challenges emerged that related to the logistical requirements of the technology innovation (e.g., setting up probeware) and to the schools' technology configurations and technical support resources. Most of these technical obstacles were overcome in long-term studies. Researchers built partnerships with participant teachers, schools, and districts so that they could address the technical challenges as they arose. Teachers and researchers also encountered instructional challenges during the first year related to classroom management and integration of the technology with science learning goals. To overcome instruction-related challenges, more than 1 year of professional development was needed. Teachers needed time to implement the technology-enhanced materials in their classroom, reflect on student work, modify their approach, and try again.

New Questions

The review raised issues that call for further inquiry, particularly issues of professional development value and technology-enhanced materials design. The first issue is discerning the value of professional development in relation to teacher experience with the technology. The added benefit of long-term professional development programs reflected both teachers' increasing experience with the technology innovation and the specific elements of the professional development program. We need more studies of long-term use of technology to disentangle these factors. Prior curriculum reform research suggests that with more experience but no professional development, teachers are likely to adapt the innovation to fit with their existing teaching methods, often a more direct instruction approach (Elmore, 1996; Sarason, 1996). Evidence is needed in the area of technology-enhanced science to see if this is the case.

Technology creates new opportunities to support teachers and administrators in using multiple forms of student data to refine science education. Technology-enhanced curriculum designers can work in partnership with teachers and school leaders to design materials that will collect, organize, and display valuable assessment student data that enable teachers and school leaders to improve their science program. Determining what data teachers and school leaders need is an important question in need of further research. As a starting point, our review suggests that the data should support teachers to respond to individual and collective student ideas and enable school leaders to create greater opportunities for teachers to play a central and ongoing role in technology-enhanced instructional refinement.

Research Collaborations

Haertel and Means concluded in 2003 that substantial funding was needed for a coordinated, large-scale research program on educational technology and learning in K–12 classrooms to understand what works and why. Our findings support the value of empirical studies conducted in multiple settings over several years. Six studies demonstrating positive impacts of professional development on student learning were conducted by National Science Foundation–funded Centers for Teaching and Learning (Fishman et al., 2003; Geir et al., 2008; Gerard, Spitulnik, et al., 2010; Lee et al., 2009; Rivet & Krajcik, 2004; Slotta, 2004). The Centers for Teaching and Learning supported multiple institutions with diverse expertise to collaborate for 5 or more years to investigate technology-enhanced inquiry science instruction. This allowed for systematic and rigorous data collection and analysis on curriculum design, leadership, teacher professional development, teacher practice, and multiple dimensions of student learning. Evidence of student learning is critical to increasing federal and state funding for professional development in technology-enhanced science and informing educators of what works. If we are to continue to improve science and technology instruction and learning, support for research programs like the Centers for Teaching and Learning is needed.

In conclusion, supporting teachers to learn from practice is one of the most powerful ways of effecting educational improvement (Darling-Hammond, 2010). Although the benefits of evidence-based practice are well recognized, it is a rare practice in most classrooms. Teachers' instructional decisions are more often based on their own prior experience (i.e., existing pedagogical content knowledge) and limited insight about students' ideas that emerge as a result of scant interactions during lectures or labs (Hoge & Coladarci, 1989). A lack of timely access to data showing students' progress in relation to instruction and a need for better preparation in applying data to instructional decisions are the main obstacles identified by the literature (Darling-Hammond & Snyder, 2000; Kerr, Marsh, Ikemoto, Darilek, & Barney, 2006). Technology-enhanced instructional materials offer new possibilities to support evidence-based instruction. A combination of high-quality professional development that supports teachers to engage in constructivist-oriented learning processes and technology-enhanced curricula that provide teachers with detailed evidence of student learning has the potential to play a transformative role in improving science education.

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