



Is science inquiry professional development effective?
A critical review of empirical research

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ABSTRACT

Educational theorists and researchers have advocated for the use of inquiry-based instruction in science classrooms. Inquiry-based instruction has the potential to enhance student understanding and engagement in science. However, most teachers are underprepared to teach science using this approach. In response, teacher professional development is commonly used to support teachers in enhancing their knowledge, changing teaching practice and improving student achievement. Unfortunately, little empirical evidence exists to demonstrate the effectiveness of teacher professional development in supporting teacher growth. A major challenge in science education today is to link teacher participation in professional development to enhanced teacher knowledge, changes in teaching practice and improved student achievement. We present a critical review of research of 14 inquiry-based professional development programs. Our review focuses on the reported outcomes of each program. Available data support our hypotheses that in-service programs which immerse teachers in authentic inquiry will more likely 1) enhance teacher knowledge, 2) prepare teachers to implement inquiry instruction and 3) lead to enhanced student understanding. Implications for future research on inquiry-based professional development programs are discussed.

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Over a decade ago science education reform documents in the United States advocated changing science teaching in precollege science classrooms from less emphasis on using direct instruction to greater emphasis on inquiry-based instruction (American Association for the Advancement of Science, 1989, 1993; National Research Council [NRC], 1996; 2000; National Science Teachers' Association Position-Statement, 1998). Although science reform efforts highlighted the importance of inquiry-based instruction, it appears that little has changed regarding how science is taught in the majority of US classrooms. Most teachers do not use inquiry-based instruction in their classrooms due to a number of issues including: perceived time constraints due to high-stakes testing; unfamiliarity with how science is practiced (Deboer, 2004); inadequate preparation in science (Krajcik, Mamlok, Hug, & 2000), or they simply do not understand what inquiry is. This problem is more apparent at the elementary and middle school levels, where teachers have little or no formal science training and lack familiarity with the fundamentals of scientific inquiry and inquiry-based instruction (Kennedy, 1998; Loucks-Horsley, Hewson, Love, & Stiles, 1998, 2003). Inquiry-based teaching is a complex and sophisticated way of teaching that demands significant professional development (Crawford, 2000, 2007). Unless teachers are supported in learning about the nature of scientific inquiry and how to create an inquiry-based learning environment in the classroom, it is unlikely that teacher practice will change.

Teacher professional development—sometimes referred to as teacher training—is a proposed method to support practicing teachers in implementing inquiry-based instruction in science (Loucks-Horsley et al., 1998, 2003; NRC, 1996). It is regarded as a cornerstone for the implementation of standards-based reform (Committee on Science and Mathematics Teacher Preparation, 2001). Recently, many professional development programs have emerged to support classroom teachers in changing their instructional approach to be more consistent with inquiry-based instruction. Millions of dollars have been spent on these programs; however, there is a paucity of empirical evidence supporting the effectiveness of teacher professional development (Smylie, 1996; Wilson & Berne, 1999). An exhaustive search did not reveal a comprehensive review of professional development programs focusing specifically on scientific inquiry. The purpose of this paper is to critically review and evaluate those empirical studies pertaining to inquiry professional development interventions. Specifically, we are interested in how professional development programs support teachers in enhancing their knowledge, changing their beliefs and practices, and if these changes can be linked to enhanced student knowledge.

We begin the review with a background section where we define the terms scientific inquiry, inquiry-based learning, and inquiry-based teaching and discuss where the confusion regarding inquiry arises. Then, we discuss the theoretical underpinnings for teaching science as inquiry and illustrate why inquiry-based instruction is considered an important part of school science. Next, we define teacher professional development and discuss the overall goals and best practices for professional development as defined by experts in the field, empirical studies, and The National Science Education Standards (NSES [NRC, 1996]). In the method section we present the criteria for our literature review; describe how articles were searched for, selected, and grouped, as well as present our analysis. We then present our critical review of the literature,

followed by a discussion of implications and findings to promote better professional development for scientific inquiry.

Background: Scientific Inquiry and Professional Development

Scientific Inquiry: Definitions & Theoretical Underpinnings

There has been much confusion in the science education community over the meaning of the term inquiry. Inquiry has been referred to as an elastic term that can be “stretched and twisted to fit people’s differing world views” (Wheeler, 2000, p. 14). This is evidenced by the fact that nearly every academic discipline has its own definition of the process of inquiry. Most teachers have encountered the word inquiry in a variety of contexts throughout their careers, including college classes, textbooks, and professional development, but they have little direct experience engaging in inquiry. Limited experience with inquiry has caused many to equate it with teaching techniques like hands-on learning, learning by doing, problem based learning or a variety of other methods that do not necessarily guarantee meaningful inquiry is occurring (AAAS, 1993; NRC, 1996). The NSES define five essential features of classroom inquiry (NRC, 2000). These features can be used by teachers to evaluate if inquiry, specific to science, is occurring in their classrooms (see Table 1).

Table 1

Five essential features of inquiry (NRC, 2000)

NSES, 5 Essential Features of Classroom Inquiry
1) Learner is involved in a scientifically oriented question
2) Learner gives priority to evidence in responding to the question
3) Learner uses evidence to develop an explanation
4) Learner connects explanation to scientific knowledge
5) Learner communicates and justifies the explanation

Some of the confusion may also exist because science education literature and reform documents discuss inquiry in several different contexts including scientific inquiry, inquiry-based learning, and inquiry-based teaching. Each of these terms has a particular meaning that when not specified may lead to misunderstandings. Here, we define each term and its relationship to science education. Scientific inquiry has been defined as, “...the diverse ways in which scientists study the natural world and propose explanations based on evidence derived from their work” (NRC, 1996, p. 23) or more simply as, “the process by which scientific knowledge is developed” (Lederman, 2004, p. 308). Scientific inquiry can also be thought of as science as practiced by scientists, or authentic scientific inquiry (Brown, Collins, & Duguid, 1989). It has been argued that classroom inquiry will never reach the level of sophistication involved in authentic scientific inquiry. By presenting classroom inquiry as equal to scientific inquiry, one skews the image of the authentic practice (Lave & Wenger, 1991). Although authentic scientific inquiry is different from classroom inquiry, classroom inquiry can be modeled after the authentic practice of science to enhance student interest and motivation (Crawford, 2000).

The NSES consider classroom inquiry as three different things; two of which are educational outcomes while the third is a teaching strategy. The educational outcomes of inquiry are composed of one's ability *to do* scientific inquiry, which includes asking and identifying questions, planning and designing experiments, using data, and connecting it with explanations; and a content area of study or the *knowledge of how scientists do their work*, for example realizing that scientists ask questions, perform different types of investigations, and produce explanations based on observations (NRC, 1996, p. 121). The third part of classroom inquiry is a *kind of pedagogy*; inquiry-based teaching concerns the pedagogy of inquiry or one's ability to employ inquiry instruction in the classroom (NRC, 2000).

Theoretical Underpinnings & the Importance of Inquiry Instruction

Most teachers do not use inquiry-based instruction in their classrooms. Many use primarily direct instruction because it reflects how they were taught (Britzman, 1991; Lortie, 1975). Direct instruction is teacher-centered and focuses on memorizing content and may have little relevance to the learner (AAAS, 1993). Reform-based teaching approaches—like inquiry—draw on constructivist views of learning (e.g. Driver, Asoko, Leach, Mortimer, & Scott, 1994). Constructivism in science education centers on the idea that learners should be engaged in answering authentic scientific questions relevant to both their lives and to scientists (Brown et al., 1989; Dewey, 1938; Schwab, 1976). Reform-based teaching focuses on active student knowledge construction instead of merely drill and the memorization of facts. Teaching science as inquiry may seem more relevant to students than other forms of science instruction like lecture or cookbook labs, because it engages students in negotiating their own understandings with science and approximates how science is practiced (Dewey, 1938). Dewey's perspective on science education focused on solving real world problems based in children's experiences. He argued for an inquiry-based, student-centered education where the role of the teacher was to guide and support students in an active quest for knowledge (Dewey, 1938). Inquiry-based instruction has potential to improve both student understanding of science and engagement in science (AAAS, 1989, 1993; NRC, 1996). Further, inquiry-based science teaching has possibilities of engaging *all* students, including those from underrepresented populations in science, in understanding and becoming motivated to learn science.

Definitions & Characteristics of Effective Professional Development

Professional development in teaching has been defined as the “sum total of formal and informal learning experiences throughout one's career from preservice teacher education to retirement” (Fullan, 1991, p. 326). Characteristics of effective professional development have been described by well recognized experts in the field of general education like Darling-Hammond & McLaughlin (1995) and more specifically in science education by Loucks-Horsley et al. (1998). These characteristics are listed in Table 2. Common features of each include engaging participants in inquiry-based learning and modeling teaching strategies, connecting professional development to classroom work, and continuity.

Table 2

Characteristics of Effective Professional Development Described by Darling-Hammond et al. (1995) and Loucks-Horsley et al. (1998)

Darling-Hammond et al. (1995)	Loucks-Horsley et al. (1998)
<ul style="list-style-type: none"> • Engages teachers in concrete tasks of teaching, assessment, observation, and reflection • Engages participants in inquiry, reflection and experimentation. • Promotes a collaboration between participants and professional developers • Connects or is coherent with classroom work • Sustaining and continues support • Connects to other aspects of school change 	<ul style="list-style-type: none"> • Emphasizes inquiry-based learning, investigations, and problem solving • Helps build pedagogical skills and content knowledge • Models the strategies teachers will use with their students • Builds learning communities where continued learning is valued • Supports teachers in leadership roles • Links to the educational system (district initiatives, state curriculum, etc..) • Changes to insure positive impact.

More recently, large scale surveys have aimed to determine the factors that make science professional development effective (Garet, Porter, Desimone, Birman, & Yoon, 2001; Penuel, Fishman, Yamaguchi, & Gallagher, 2007). Garet et al. (2001) conducted a national probability study of 1,027 teachers and reported six characteristics of effective math and science professional development programs. Penuel et al. (2007) surveyed 454 teachers to determine characteristics of professional development that affect teacher knowledge and implementation (see Table 3 for characteristics). Several of the features determined in these studies confirm ideas suggested by Darling-Hammond et al. (1995) and Loucks-Horsley et al. (1998); particularly, engaging participants in inquiry-based learning and modeling teaching strategies, connecting professional development to classroom work, continuity, and duration of the activity. Additionally, these studies suggest other important characteristics of professional development for science teachers such as focusing on science content knowledge and the importance of discussing how to integrate activities in the classroom.

In addition to experts in the field of professional development and surveys, reform documents such as the NSES provide guidelines for professional development. The NSES suggested that professional development programs in science, “explicitly attend to inquiry—both as a learning outcome for teachers and as a way for teachers to learn science subject matter” (NRC, 2000, p. 112). Furthermore, the standards call for professional development programs to help teachers learn how to teach through inquiry.

Table 3

Characteristics of effective professional development reported by Garet et al. (2001) and Penuel et al. (2007)

Garet et al. (2001)	Penuel et al. (2007)
<ul style="list-style-type: none"> • Focuses on content knowledge • Provides opportunities for active learning • Coherency with other activities • Form of activity (workshop vs. study group) • Collective participation of teachers from same school • Duration of activity 	<ul style="list-style-type: none"> • Discusses alignment with local, state, and national standards • Engages teachers in aligning activities with standards • Emphasizes content of particular curriculum during professional development • Ongoing, coherent professional development • Reform-based professional development

Method

Selection of Studies for Review

A keyword search using the terms “science inquiry” and “professional development” was conducted in Google Scholar, the Educational Resources Information Center (ERIC), and Wiley InterScience databases. These searches produced a great number of articles related to science inquiry professional development. In order to narrow the scope of the review, we selected only empirical studies published in major international journals of science education subsequent to the publication of the NSES standards. Additionally, all articles selected for review came from singular non aggregate studies where outcome data were reported on teacher knowledge, changes in teacher beliefs or practice, or student achievement. A subsequent search was performed in data bases of the *Journal of Research in Science Teaching (JRST)*, *Science Education (SE)* and the *International Journal of Science Education (IJSE)* to ensure appropriate studies were included. Several other articles were located in bibliography searches using a snowball sampling technique (Kratwohl, 1998). Clearly, many papers have been presented at conferences on a similar topic, but we excluded these studies in favor of those published in highly-rated peer-reviewed journals (see Table 4 in Appendix for studies included in this review).

Analysis of Studies

Our analysis of the studies was grounded in our beliefs and biases as former teachers, teacher educators, and professional developers. In attempting to remain as objective as possible we relied on science education literature and reform documents in order to develop our analysis scheme. Using a combination of expert opinion, surveys on professional development in science/math, and reform documents, we developed a list of nine common features of successful science inquiry professional development programs. The features included in this list are: duration, continuity, coherency with standards, development of lessons, modeling inquiry, authentic experiences, reflection, transference, and content matter. Although our list is not identical to the characteristics mentioned above, we used these documents to inform our

understanding of the features of successful professional development (see Table 4). Each of these features is now explained. *Duration* refers to the amount of time allotted for the professional development. It is reported in hours or weeks (weeks if the program completed a full, 40-hour work week). *Continuity* indicates programs that provided continued support for teachers, either through school year sessions, classroom visits focused on supporting teachers, or remote support. *Coherency* refers to professional development programs that aligned with local, state, or national standards. *Developed Lesson* denotes programs where teachers designed inquiry lessons for their classrooms. *Modeled Inquiry* means the program modeled inquiry with the teachers during the professional development. *Authentic Experience* refers to professional development programs where teachers conducted an inquiry study that was not predefined. *Reflection* refers to programs where teachers were given the explicit opportunity to reflect on their experience. *Transference* pertains to programs where there was explicit discussion about enacting the curriculum in the classroom. Finally, *Content Matter* indicates the professional development program focused on science subject matter and content learning for teachers.

Once the studies were selected, each article was carefully read in order to answer the following questions:

- 1) Are the programs aligned with critical features outlined in this review?
- 2) Are the findings of each of these studies robust?
- 3) What do these findings tell us about science inquiry professional development in general?

Results & Discussion

Alignment with Critical Features of Effective Professional Development

Duration. One feature reported to have impact on the outcome of professional development is duration (Garet et al., 2001). The inquiry professional development studies critiqued in this review range in length from four or five days to six weeks; additionally, one program did not report the total time of professional development (see Table 4). Although there is no specified amount of time for effective professional development, programs need to provide teachers enough time to fully process and address the doubts and misconceptions they have regarding inquiry. Four or five days may be adequate amount of time to help teachers understand certain facets of inquiry if this is all the program is trying to accomplish. However, in addition to focusing on inquiry, the two shortest programs also spent time on literacy development for English language learners and other topics (Lee, Hart, Cuevas, & Enders, 2004; Lee, Maerten-Rivera, Penfield, LeRoy, & Secada, 2008). Partitioning an already brief program may not allow teachers adequate time to fully address doubts and misconceptions they have regarding inquiry.

Continuity. Eleven of the fifteen programs critiqued provided continued support (see Table 4). Continuity is important because it gives teachers a chance to ask questions and interact with professional developers as well as their colleagues. There are a variety of ways to support teachers after an initial workshop including classroom visits, reconnects where teachers and developers physically meet, and various kinds of remote support, like chat groups and threaded discussions. Remote support such as chat groups and threaded discussions may also serve as a way to promote collective teacher participation for professional development programs that draw in teachers from a variety of geographic areas, creating a virtual professional community. Unfortunately, the two shortest programs and the program that did not report the duration of

professional development also did not appear to provide continued support. It seems that programs with short duration could make up for lack of time with increased follow-up support for teachers when they return to their schools.

Coherency. All 15 programs critiqued aligned their workshops with either state or national standards. This finding is encouraging because it shows that professional developers are paying attention to the features of successful professional development identified in science education literature and reform documents. Clearly, teachers will be more likely to enact a curriculum if they see it as relevant to their everyday work.

Developed lessons. Only six of fifteen programs reviewed had teachers develop lessons (see Table 4). One program expected teachers to bring in problematic lessons and adapt them to be more consistent with inquiry (Lotter, Harwood, & Bonner, 2007). This explicit approach helped teachers learn how to develop their own inquiry lessons and allowed them to collaborate with colleagues and with professional developers. Holliday (2004) criticized reform documents for not being explicit enough about inquiry teaching. Professional developers should also take note of this recommendation. Just because teachers are able to enact an inquiry lesson developed by others does not mean they will be able to develop inquiry lessons on their own. Professional development should focus on supporting teachers in adapting existing lessons and creating new lessons to reflect the essential features of inquiry.

Modeled inquiry. Fourteen of the fifteen programs reviewed modeled inquiry in their professional development (see Table 4). Some of the programs focused more on modeling inquiry than others. The longer duration programs that had an emphasis specifically on inquiry gave teachers the opportunity to model entire curriculums (Taitelbaum, Mamlok-Naaman, Carmeli, & Hofstein, 2008) while shorter programs that focused on several topics spent less time on modeling inquiry and often gave practice tasks where teachers focused on specific process skills (Lee et al., 2004). As noted earlier, the essential nature of inquiry is often misunderstood by teachers (Deboer, 2004). Because of this, modeling inquiry with teachers during professional development is important to help them understand the essential features of classroom inquiry. Clearly, if teachers are expected to teach using inquiry they will need to work through content matter in this way (McDermott & DeWater, 2000). Programs that offer more opportunity for teachers to model inquiry will likely better prepare teachers to do inquiry science with their students.

Authentic experience. Only four of the studies critiqued engaged teachers in authentic inquiry—these experiences paralleled the actual work of scientists (see Table 4). One program, not included in the four that engaged teachers in authentic inquiry, nearly made the list, however, teachers worked in labs helping scientists instead of conducting their own investigations (Lotter et al., 2007). The fact that only four studies engaged teachers in authentic inquiry is problematic. Constructivist views of learning and situated cognition advocate learning in specific contexts and allowing adequate time to reflect and draw on past experiences (Brown et al., 1989; Lave & Wenger, 1991). It is predicted that teachers who have an authentic inquiry experience, similar to what they will later enact in their classroom, will be better able to communicate that experience and related concepts to their students (Dubner et al., 2001).

Reflection. Twelve out of fifteen of the programs critiqued reported using teacher reflection in their professional development. Literature on teacher professional knowledge points out the value of reflection to teacher change (Tobin, Briscoe, & Holman, 1990; Tobin & LaMaster, 1995). Reflection is an important aspect of teacher professional development because experience alone will not lead to teacher learning and teacher change (Loughran, 2002). Inquiry professional development programs should encourage teachers to reflect on their experiences. Without including explicit reflection as part of professional development experiences it is unlikely that teacher learning or change will occur.

Transference. Twelve out of fifteen programs reviewed actively supported teachers in discussing transference into their classrooms. Explicit discussion about how one will enact workshop materials in the classroom is an essential feature of inquiry professional development. There is no classroom environment or teacher that is identical. Allowing workshop time for teachers to discuss these differences with colleagues and professional developers ensures that teachers will feel comfortable enacting the curriculum in their classrooms. Additionally, discussions on transference allow teachers to consider how enactment may look in their classroom.

Content matter. Ten out of fifteen of the programs reviewed in this study focused on specific subject matter knowledge including teachers understanding of science concepts like chemistry, NOS, or inquiry. Garet et al. (2001) suggested that the degree of subject matter focus is an important feature of professional development in the sciences. Subject matter knowledge is considered important because many teachers lack specific content matter teaching skills. If this content matter does not reach teachers they will likely be uncomfortable with the material and have difficulties teaching when they attempt to enact the material.

Robustness of the Findings

Inquiry professional development programs reported a range of findings including enhanced teacher knowledge, enhanced teacher practice, change in teacher belief, and enhanced student knowledge as a result of the professional development intervention (see Table 4). Each of the programs critiqued reported on one or more of these findings. Interestingly, none of the programs reviewed reported outcomes on all four of these categories. This finding is problematic because it indicates that none of these studies has been able to link enhanced teacher knowledge to change in beliefs, change in practice, and enhanced student knowledge. The remainder of this section critiques findings from each of the articles reviewed based on the categories of the findings reported in the study.

Enhanced teacher knowledge. Enhanced teacher knowledge including content knowledge, knowledge of NOS, and inquiry was measured in a variety of ways including instruments resembling tests, interviews, and questionnaires. Seven of the studies reviewed reported enhanced teacher knowledge as a result of the professional development (see Table 4). Three of these studies used a pre and post instrument similar to a written test to demonstrate an improvement in teacher content knowledge (Basista & Mathews, 2002; Jeanpierre, Oberhauser, & Freeman, 2005) or in science process skills (Radford, 1998). Akerson & Hanuscin (2007) employed an open response questionnaire and interviews, while Luft (2001) used interviews to

document enhanced teacher knowledge on views of inquiry and nature of science. Another study used pre/post surveys and interviews to report on enhanced teacher knowledge of inquiry (Shepardson & Harbor, 2004). The methods discussed in each of these studies appeared thorough. Only one study employed teacher self-report data as evidence of enhanced teacher knowledge (Lee et al., 2004). This study concluded that teachers felt more knowledgeable about inquiry after the intervention. It is difficult to gauge what more knowledgeable truly means. Teacher self report has been referred to as a suspect methodology that provides “unconvincing evidence of real gains” (Fretchling, Sharp, Carey, & Vanden-Kieman Westat, 1995, p. 33). This finding could have been bolstered by using a pre/post instrument, an interview, or observing the teachers’ use of inquiry in the classroom. Observations were employed in this study, but none pertained directly to the teacher and inquiry. In general, studies that actively measured teacher understanding before and after the professional development intervention or used multiple methods to verify findings appeared more robust.

Change in teacher beliefs. Change in teacher beliefs concerning the importance of inquiry and confidence in implementing inquiry were measured using interviews, questionnaires, and classroom observations. Three studies reported on changes in teacher beliefs as a result of the professional development. Lee et al. (2004) used a Likert-style questionnaire to show a statistically significant change in response to the importance of inquiry following the professional development. However, classroom observations indicated that the change in belief did not affect classroom practice. Conversely, another study that used a questionnaire to report that teachers felt better prepared verified this finding with informal classroom observations and reviewing teacher portfolios (Basista & Mathews, 2002). A final study examined teacher pedagogical philosophy in pre/post interviews. This study indicated that changes in beliefs are more common in new teachers than veteran teachers. However, this study found that veteran teachers were more likely to change teaching practice (Luft, 2001). These results highlight two things. First, very few studies systemically assess teacher beliefs. Second, assessing teacher beliefs is a difficult endeavor. Measurement of teacher beliefs is not necessarily indicative of teacher practice. Further work should focus on alternative ways to assess teacher beliefs other than solely teacher self-report.

Change in teacher practice. Enhanced teacher practice of inquiry in the classroom or ability to teach using inquiry was measured using both teacher self report data and classroom observations. Eleven of the studies reviewed reported on teacher practice (see Table 4). Three studies employed teacher self report data as evidence of enhanced practice of inquiry (Jeanpierre et al., 2005; Lee et al., 2004; Young & Lee, 2005). Both Jeanpierre et al., (2005) and Lee et al. (2004) also employed classroom observations to confirm teacher self report data. Findings from Lee et al. (2004) conflicted with teacher self-report data indicating a lack of actual change in classroom practice as a result of the intervention, while observations by Jeanpierre et al., (2005) confirmed teacher self report data. Equivocal results from teacher self report confirms Fretchling et al. (1995) concern that teacher self report data alone may not actually reflect what is happening in the classroom. In order to assess changes in classroom practice it is necessary to conduct pre and post observations of teacher classroom practice. The remaining eight studies all used classroom observation to report on enhanced teacher practice of inquiry.

Enhanced student knowledge. Enhanced student knowledge including content knowledge, knowledge of NOS, and inquiry was measured in several different ways including instruments resembling tests, interviews, and teacher perception of student knowledge. Eight out of the fifteen studies reported on enhanced student knowledge (see Table 4). Six of the studies used instruments similar to tests to report gains in student content knowledge or inquiry skills (Johnson, Kahle, & Fargo, 2007; Lee et al., 2008; Marx et al., 2004; McNeill & Krajcik, 2008; Radford, 1998; Young & Lee, 2005). The setup of two of these studies resulted in methodological problems. One study had no control group (Lee et al., 2008). This made it difficult to ascertain if enhanced student knowledge was due to the professional development program or maturation. A second study only used a post-test (Johnson et al., 2007). Because of this, it was impossible to tell if teachers' involvement in professional development affected their students. The remainder of the studies mentioned above appeared thorough. (Akerson & Hanuscin, 2007) used pre and post interviews to document enhanced student knowledge of NOS. A final study used teacher perception to report on enhanced student ability at developing researchable questions, designing and conducting investigations, and sharing investigation results (Luft, 2001). Findings from this study would have been more robust if they had combined teacher report with classroom observation.

What do these Findings Tell Us about Science Inquiry Professional Development?

Experts in science education and science reform documents have advocated inquiry as a preferred science teaching approach and as a learning outcome for students. It has been suggested that professional development is needed to support teachers in learning about inquiry and teaching science as inquiry. In conducting this review we were interested in how recent, inquiry professional-development programs supported teachers in enhancing their content knowledge, changing their beliefs and practices, and if these changes can be linked to enhanced student knowledge. Currently, there have been very few empirical studies (15) related specifically to science-inquiry professional-development programs published in major peer-reviewed journals in science education.

None of the articles reviewed in this study have linked enhanced teacher knowledge to changes in teacher beliefs, practice, and enhanced student knowledge. Moreover, the majority of these articles only focused on one or two of these outcomes. An important challenge in science education research is to establish a relationship between teacher learning to student learning. This connection can be used to either confirm or reject expert opinion regarding inquiry teaching as a preferred instructional practice. Without considering each of these four variables, studies connecting enhanced teacher knowledge to enhanced student knowledge will have very little explanatory power (Zeichner, 2005). In exploring this relationship of variables, researchers must take into account the complexity of teacher practice. In addition, it is important to consider teachers' predispositions to an inquiry oriented teaching approach, since teachers come to professional development programs with years of experiences in teaching (Kagen, 1992). It may also be important to consider the filtering effects of teachers' prior beliefs (Yarrick, Parke, & Nugent, 1997). Researchers should recognize that connecting teacher learning to student learning needs to be studied with the most robust methods available. For instance, in attempting to access teacher beliefs, a researcher might use a Likert-style questionnaire in order to understand a

phenomenon from the teacher's perspective. However, teacher self-report should be followed-up with classroom observations and teacher interviews in order to verify teacher self-report.

Conclusions and Implications

In closing, there is a need for more published empirical research on effectiveness of professional development models related to scientific inquiry. Many studies have been presented at annual conferences but few have yet to reach publication. Existing studies reviewed in this paper report a range of outcomes including enhanced teacher knowledge, changes in teacher beliefs and practice, and growth in student knowledge; however, no existing study reports on all of these. Future studies should be designed to investigate the connection between teacher knowledge, changes in teacher beliefs and practice, and student knowledge. Additionally, although it is acknowledged that there is no one formula for teacher professional development (Loucks-Horsley et al., 1998, 2003), programs reviewed in this study indicate alignment with features of effective professional development defined in the science education literature. However, no single study reviewed incorporated all the features of effective professional development. Future studies should attempt to explore which of the nine features of effective professional development identified in this paper are most critical for teacher growth.

A limitation of this critical review is that we did not consider the extent of the interactions between various features of effective professional development defined in the science education literature. For instance, is there a relationship between the duration of a program and if scientific inquiry was modeled? This was beyond the scope of our study. We suggest that a future review might look at the interactions between variables to determine the most effective combinations of features to be employed in professional development programs.

Effective inquiry professional development should support teachers in enhancing their knowledge and changing their practice. Clearly, teachers who lack content knowledge or pedagogical knowledge will have difficulty teaching science as inquiry. If teachers are going to be asked to teach using inquiry approaches they will need to be comfortable with science content knowledge, understand what inquiry is, have experience both conducting scientific inquiry and teaching using inquiry-based approaches, and have practice adapting lessons to be congruent with inquiry-based instruction. With this in mind, it may be beneficial to begin looking for a framework to support teachers in learning about how to teach science as inquiry. Although there have been models published for supporting teachers in implementing reform-based teaching (e.g. Marx, Blumenfeld, Krajcik, & Soloway, 1997, 1998; Fishman, Marx, Best, & Tal, 2003) these models did not include an authentic inquiry experience as a component. Other models (e.g. Shepardson et al., 2004) have provided authentic inquiry experiences, but did not support teachers in developing their own inquiry-based lessons. We argue that a framework for effective inquiry professional development will provide a structure for challenging teachers to examine their knowledge and beliefs and reflect on their teaching practice, allow teachers the opportunity to experience authentic scientific inquiry in meaningful contexts similar to how they will teach in their classrooms, support teachers in developing their own inquiry-based lessons, and focus on both content knowledge and pedagogical knowledge.

Appendix

Table 4

Shows alignment with the critical features of professional development and the reported findings of each of the studies reviewed

Study	Goal	Level	Time	Continued	Coherence	Develop Les	Modeled Inq	Authentic Exp	Reflect	Transference	Content Matter	(+) Teach Know	Δ Belief	Δ Practice	(+) Stud Know
Lee (2004)	TB, Tpr	E	4 days	n	y	n	y	n	n	y	y	y, SR	y, SR	y-SR N-Ob	x
Lee (2008)	SA	E	5 days	n	y	n	y	n	y	n	y	x	x	x	y-NC
Marx (2004)	SA	M	1 wk +	y	y	n	y	n	y	y	n	x	x	x	y
McNeill (2008)	TPr, SA	M	1 wk +	y	y	n	y	n	n	y	n	x	x	y	y
Young (2005)	SA, Tprep	E	NR	n	y	n	n	n	n	n	n	x	x	y-SR w/Ob	y
Taitelbaum (2008)	Tpr	S	61+hrs	y	y (INQ)	n	y	n	y	y	y	x	x	y	x
Luft (2001)	TB, Tpr	M/S	6 days +	y	y (INQ)	y	y	n	y	n	y	y	y (new)	y	y
Lotter (2007)	TB, Tpr	S	2 wks+	y	y	y	y	n	y	y	y	x	x	y	x
Ackerson (2007)	TK, TB, Tpr	E	84 hrs	y	y	y	y	n	y	y	y	y	x	y	y
Johnson (2007)	SA	M	198 hrs	y	y	y	y	n	y	y	n	x	x	x	y
Basista (2002)	TK, TB	M/S	72 hrs	y	y	y	y	n	y	y	y	y	y, SR	x	x
Jeanpierre (2005)	TK, Tpr	S	100 hrs	y	y	n	y	y	y	y	y	y	x	y-SR w/Ob	x
Shepardson (2004)	TK, Tpr	E-S	4 wks	y	y	n	y	y	y	y	y	y	x	y	x
Radford (1998)	TK, TAt, SK, SAt	E-S	3 wks+	y	y	n	y	y	y	y	y	y	x	y	y
Blanchard (2008)	TK, Tpr	S	6 wks	n	y	y	y	y	y	y	n	x	x	y	x

Note. TB = Teacher Beliefs, Tpr = Teacher Practice, SA = Student Attitude, Tprep = Teacher Preparation, TK = Teacher Knowledge, TAt = Teacher Attitude, SK = Student Knowledge, E = Elementary, M = Middle, S = Secondary, SR = Self Report, Ob = Observation, NC = No Control Group

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