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Effects of Professional Development on Teacher Pedagogical Content Knowledge, Inquiry Teaching Practices, and Student Understanding of Interdisciplinary Science

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ABSTRACT

Systematic studies on the effectiveness of in-service teacher professional development (PD) are important for science education research and practice. Previous studies have mostly focused on certain outcomes of PD, for example, the effectiveness of PD for improving teachers' knowledge or students' learning outcomes. This study, however, explores multiple outcomes of PD, from teachers' change in knowledge and practice and how teacher change influences students' beliefs and ultimately their understanding of interdisciplinary science concepts. The sample included 509 students from 23 classrooms within 5 elementary/middle schools. The results showed that teacher attendance in professional learning communities and interdisciplinary science research related positively to teachers' scores on a pedagogical content knowledge test. Students whose teachers had more than 150 PD hours in the past academic year performed significantly better on an interdisciplinary science test. Follow-up analyses suggested that student understanding of the nature of science possibly mediates the positive effect between PD hours and student understanding of interdisciplinary science concepts.

KEYWORDS
hierarchical linear model; in-service professional development; interdisciplinary science and engineering partnership; mediation effect; student understanding of interdisciplinary science; teacher knowledge; teacher practice

Many efforts have been made to reform science education to improve students' science achievement in the past few decades, from *Science for All Americans* (Rutherford & Ahlgren, 1990) to the present framework of the Next Generation Science Standards (NGSS; National Research Council, 2012). One focus of *Science for All Americans* is to emphasize connections between traditional science subjects and more conceptual understanding and thinking skills rather than the memorization of facts and procedures (Bybee, 1995). The NGSS takes another major step forward through its expectations for student performance in terms of three interconnected dimensions: science and engineering practices, crosscutting concepts (CCs), and disciplinary core ideas (NGSS Lead States, 2013). The NGSS are deeply rooted in interdisciplinary science inquiry (ISI), learning sciences, and science education research, and a number of states have already adopted the standards. As a result, science teachers are facing the challenge of implementing such standards, and professional development (PD) is needed to help teachers accomplish what they are required to do.

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Despite the fact that the concept of ISI has been promoted for the past few decades leading to the NGSS, little research is available on PD for such inquiry. The purpose of the study reported in this article is to explore possible relations among features of a PD program in ISI, teachers' pedagogical content knowledge (PCK), inquiry teaching practices, and students' understanding of interdisciplinary science concepts within the project. The specific research questions are as follows:

(1) What is the relationship between PD in ISI and teachers' PCK?
(2) What is the relationship between PD in ISI and student report of teacher inquiry teaching practices?
(3) What is the relationship between PD in ISI and students' understanding of interdisciplinary science concepts?
(4) Is there any possible mediation effect between PD in ISI and students' understanding of interdisciplinary science concepts through teachers' PCK and students' understanding of the nature of science (NOS)?

Literature review

Teacher knowledge and practices

The focus of teacher knowledge has shifted from separate content knowledge and pedagogical knowledge to Shulman's (1986) concepts of subject matter knowledge (SMK) and PCK. It is reasonable to say that the concept of teacher knowledge continues evolving, but SMK and PCK remain essential to effective science teaching (Zeidler, 2002). According to Shulman, PCK represents the knowledge required to make subject matter accessible to students, and SMK refers to a teacher's quantity, quality, organization of information, and conceptualization in their teaching area. The two types of teacher knowledge are key components of teacher competences that affect student progress (Diamond, Maerten-Rivera, Rohrer, & Lee, 2014; Kleickmann et al., 2013; Sadler, Sonnert, Coyle, Cook-Smith, & Miller, 2013).

According to Abell (2007), the development of a teacher's PCK is grounded mostly in three other knowledge bases: (a) SMK; (b) pedagogical knowledge; and (c) knowledge of context, which includes knowledge of communities, schools, and students' background. Teachers transform SMK into instruction delivered to their students in a meaningful way based on their pedagogical knowledge. This instruction is situated in the teacher's knowledge of context. Different aspects of PCK have been identified since Shulman introduced the model, and they have been revised and extended in the past few decades (Korthagen, Loughran, & Russell, 2006). For example, Magnusson, Krajcik, and Borko (1999) conceptualized PCK for science teaching as consisting of (a) orientations toward science teaching, (b) knowledge and beliefs about science curriculum, (c) knowledge and beliefs about students' understanding of specific science topics, (d) knowledge and beliefs about assessment in science, and (e) knowledge and beliefs about instructional strategies for teaching science (p. 97). Similarly, Park and Oliver (2008) identified five distinctive dimensions in a working definition of PCK, namely, (a) orientation toward teaching science, (b) knowledge of curriculum, (c) knowledge of learners, (d) knowledge of instructional strategies, and (e) knowledge of assessment. These PCK models can form a framework for assessing teachers' PCK.

Science inquiry is defined as engagement in the pursuit of scientific questions via data collection, experimentation, exploration, and discussion; it is recommended that teachers use the strategy of science inquiry and diverse approaches to teaching science (National Research Council, 2000). Having sufficient PCK helps teachers carry out instruction in science inquiry; however, factors including inadequate time and lack of confidence and competence in conducting science inquiry have been identified as barriers to implementing science inquiry in teacher practices (G. Smith, 2014).

PD and its relationships with teacher knowledge/practices and student learning outcomes

According to van Driel, Meirink, van Veen, and Zwart (2012), PD refers to the procedures and activities designed to consolidate teacher professional knowledge, skills, and attitudes in order to further improve student learning. This study adopted Desimone's (2009) conceptual framework of features of effective PD and how PD can improve teacher and student outcomes. The features of effective PD in Desimone's study are consistent with the widely accepted features of PD in science education, which consist of (a) content focus—opportunities for teachers to enhance their content knowledge and PCK; (b) active learning—opportunities for teachers to engage in active learning; (c) coherence—alignment with teachers' personal beliefs and schools' and districts' priorities; (d) duration—prolonged activity span; and (e) collective participation—learning communities within the same department, grade, or school (e.g., Borko, 2004; Heller, Daehler, Wong, Shinohara, & Miratrix, 2012; Wilson, 2013). Furthermore, Desimone's framework suggests four mechanisms for improving outcomes of teachers and students: (a) Teachers participate in effective PD, (b) the PD increases teachers' knowledge and changes their attitudes and beliefs, (c) changes in teachers' knowledge/attitudes improve their classroom practices, and (d) changes in practices promote increased student learning.

A number of studies have been conducted on the relationship between PD and teacher knowledge/attitudes and practice. A well-designed PD with the aforementioned features could improve teachers' knowledge (Diamond et al., 2014; Heller et al., 2012), attitudes (Supovitz & Turner, 2000; van Aalderen-Smeets, Walma van der Molen, & Asma, 2012), and practices (Banilower, Heck, & Weiss, 2007; Garet, Porter, Desimone, Birman, & Yoon, 2001; G. Smith, 2015). Teacher knowledge and practices were major mechanisms for improving student science learning (Wilson, 2013); thus, the development of science teacher knowledge and practice is essential. Some other studies involved investigations of relationships between student outcomes and PD without examining changes in teachers (Blank, de las Alas, & Smith, 2007; O. Lee, Deaktor, Enders, & Lambert, 2008; Roth et al., 2011).

Few studies have focused on the relationships among PD, teacher knowledge, and student learning outcomes. Diamond et al. (2014) proposed a model in which PD positively affects teacher science SMK test results, which in turn influence student learning outcomes. Based on the model, they designed an experiment and found that teachers in the treatment group with PD scored higher on an SMK test than their peers in control groups, and students whose teachers had higher SMK performed better on science tests, though the variance in student test results explained by their teachers' SMK results was small (6%). Heller et al. (2012) reported how three different PD interventions, namely, analyzing teaching cases, looking at student work, and metacognitive analysis, affected teacher and student learning outcomes. The results showed significant gains in teacher SMK in the three intervention groups compared with teachers in the control groups, who received project orientation and meetings of the same amount of time. No difference was found among the three intervention groups in teacher SMK, which partially accounted for student science test results.

In summary, PD has great potential for improving teacher SMK and classroom practice when the PD is designed and implemented properly. Previous empirical studies have shown positive effects of PD on teacher SMK and practice. Although teacher SMK could directly affect practice in the classroom, the latter is more complex in nature and requires a longer time to change. Furthermore, teacher SMK and classroom practice can have a major impact on student learning outcomes in science. Adequate SMK and appropriate classroom practice of teachers often lead to better science performance among students. Thus, the chain effect of PD on teacher SMK and practice, and then on better student learning, is reasonable. Few studies have explored such chain effects and provided empirical evidence to support the positive chain effects of PD.

There are also a few issues that have not been resolved in previous studies. First, most studies have focused on teacher SMK and its influence on student learning outcomes; therefore, more empirical evidence is needed to link PD, teacher PCK/classroom practice, and student learning outcomes. Second, measures of teacher knowledge/practice mainly rely mostly on tests and teacher self-evaluations; student-reported teacher practices could provide different perspectives on the effect of PD. Third, previous studies have focused only on a specific content area or student grade level, such as fifth graders' understanding of electricity; few studies have addressed student interdisciplinary science understanding as a learning outcome. Finally, although some relationships from PD to student science learning outcomes have been studied (e.g., how PD affects teacher SMK and then influences student learning outcomes), the relationships between teacher PCK involving interdisciplinary science and student understanding of interdisciplinary science concepts have not been explored. The present study intends to fill these gaps.

Definition of ISI

The definition of ISI used in this study is based on our early work, in which we proposed a framework of ISI based on the literature and interviews with scientists and observations of teachers (Authors, 2013). The framework focuses on the universality of science and the connection between science and mathematics/engineering. It is consistent with scientists' view of science inquiry, science and engineering practices, and interdisciplinary concepts of science. Furthermore, ISI stresses that the nature of today's science is interdisciplinary and that it is driven by the nature of problems, questions, and constant development of technology (National Academy of Sciences, National Academy of Engineering, & Institute of Medicine, 2005). The framework is also aligned with the NGSS, which uses the term *science and engineering practices* instead of *process skills* and emphasizes CCs in addition to disciplinary core concepts. The CCs in the NGSS blur the lines between the traditional science and engineering disciplines, thereby highlighting the interdisciplinary nature of science and engineering practices.

Method

This study took place within the context of the Interdisciplinary Science and Engineering Partnership, a National Science Foundation–funded 5-year PD program. The aim of this program was to improve the quality of science teaching and learning through promoting interactions between science, technology, engineering, and mathematics (STEM) in 12 low-performing public schools within a large urban school district in the northeastern United States.

Data sources and samples

The data were collected from four sources as shown in Table 1: teacher PD records and surveys from Summer 2012 to 2014, teacher PCK tests in Summer 2013 and 2014, student surveys in three successive semesters, and student interdisciplinary science concept tests in Fall 2013 and Spring 2014. The data from Summer 2014 to 2016 were still under processing from the external evaluator, and they would be be used in a future study.

The participating teachers volunteered to join the program, and each school included a coordinating teacher who had extra responsibility to coordinate activities with other teachers within the school. The teachers were able to propose various summer research topics as PD activities based on their interests and join professional learning community (PLC) sessions during the following academic year. Furthermore, the teachers were asked to take a PCK test every summer, and a student interdisciplinary science concept test was administered to their students at the beginning and end of the academic year. In terms of students, the interdisciplinary science concept test results of fourth through eighth graders were based on one instrument, and those of ninth through 12th graders were based on a different instrument; thus, results of primary/middle and high schools were not comparable. Thus, the present study only focused on fourth through eighth graders when analyzing effects on student learning outcomes.

This study used data from teacher PD from Fall 2012 to Summer 2014, teacher PCK tests, student surveys, and tests in Fall 2013 and Spring 2014 to conduct the analysis. In the analyses of the relationship between PD and teacher PCK test results, data from all 93 teachers from 12 schools were included. However, in the analyses of the effects of PD on student science understanding, only elementary/middle school students and their teachers were included for reasons given previously. Therefore, the latter analyses consisted of data from 509 students from Grades 4 to 8 in 23 classrooms nested in five schools.

Table 1. Timetable of research design.

Source	Summer 2012	Fall 2012	Spring 2013	Summer 2013	Fall 2013	Spring 2014	Summer 2014
Teacher							
PD record	✓	✓	✓	✓	✓	✓	✓
PCK test				✓			✓
Student							
Survey			✓		✓	✓	
Science test					✓	✓	

Note. PD = professional development; PCK = pedagogical content knowledge.

Features of the PD program

Summer experiences

The summer PD activities included three subcategories: interdisciplinary research, science curriculum study, and a college course in physics and engineering. The majority of teachers conducted interdisciplinary research aligned with the university's strategic strengths, such as integrated nanostructured systems and molecular recognition in biological systems bioinformatics. The teachers were required to submit an ISI research plan, in which the research questions should have been closely connected to the science subject they were teaching (content focus), and then conducted the research under the supervision of STEM faculty of the university. The goals of the summer research were to enhance teachers' SMK and understanding of NOS, particularly the nature of interdisciplinary science, through experiencing ISI. The curriculum study group, facilitated by university STEM faculty, focused on integrating other curricula, such as computer science and literacy, into science standards; developing resources; and designing new courses. A few teachers participated in a graduate credit-bearing summer course hosted by a local college in physics and engineering. Both the curriculum study and the summer course had a focus on NOS in addition to STEM SMK. All teachers were also required to prepare a poster presentation on their summer experiences with a focus on their improved understanding of SMK and NOS.

PLCs

The PLCs were offered by the educational research team, and the sessions were organized as monthly events over the academic year. Specifically, they consisted of six 2.5-hr workshops throughout the year (duration); all workshops were intended to facilitate teacher implementation of ISI in the classroom (coherence). A typical sequence of workshops started with the introduction of an ISI framework with a focus on NOS, proceeded to workshops on specific strategies for implementing ISI in different science curricula (which included connections between ISI and current science standards, engineering design in ISI, and school-wide ISI implementation), and finally ended with teachers' reflection and sharing of their 1-year experience of integrating ISI into their classrooms. The form of learning included lecture, group activities, group discussion (collective participation and reflection), and hands-on activities (active learning). Between workshops, participating teachers from the same school formed learning communities to exchange ideas and support one another's implementation of ISI; these within-school learning communities were facilitated by the school coordinating teachers. Graduate students in STEM majors and science education also participated in the school-based communities and provided ongoing support in teachers' classrooms to implement ISI.

Measures

Teacher PCK tests

The teacher PCK tests in this study involved Magnusson et al.'s (1999) knowledge and beliefs about students' understanding of specific science topics/concepts in which SMK is an important aspect. The PCK test of chemistry was developed by the Assessing the Impact of the Math Science Partnerships: K-8 Science project at Horizon Research, Inc. (Trygstad, Banilower, Smith, & Nelson, 2014). The PCK test of biology, earth science, and physics was developed by the Assessing Teacher Learning About Science Teaching project at Horizon Research, Inc. (P. S. Smith, 2010). The average reliability of these tests in terms of Cronbach's alpha was .84. The questions covered teacher SMK and the teacher's knowledge of learners. For example,

> A teacher asks: "What must be true about the net force acting on the paper clip?" A student responds: "The net force acting on the paper clip is upward because the magnet is still pulling up on the paper clip." What does this response tell you about this student? (Physics, Item 8)

The elementary/middle school science assessments consisted of eight items from the pedagogy of science teaching test Thinking About Science Teaching that related to teaching science to Grades 1 through 8. The responses to the items related to four basic pedagogies, namely, (a) didactic direct, (b) active direct, (c) guided inquiry, and (d) open inquiry (Cobern et al., 2014). The measures pertained to the following PCK components: orientation toward teaching science and knowledge of instructional strategies, from the very traditional method at one end of the continuum to open inquiry at the other end. Although these measures did not measure the full construct of PCK, they tapped into some important aspects of teacher PCK.

Student interdisciplinary science concept test

This instrument contained 20 multiple-choice items targeting the six CCs, for example, patterns and cause and effect. The concepts have application across all domains of science and are foundations of science and engineering practices. The items were from three sources, namely, the Science Attitudes, Skills, & Knowledge Survey: Form 1–3 (Lawson, 2000), Discovery Inquiry Test (Kahle & Rogg, 1997), and Ohio Achievement Tests: Grade 5 Science Student Test Booklet (Ohio Department of Education, 2007, 2010, 2011). The instrument was validated through Rasch modeling using the same sample of students, and the results showed that the measure was valid and reliable (Rasch item reliability = 0.98, person reliability = 0.62). Detailed analyses can be found in Authors (in press).

Teacher PD record

Teachers could choose a 4- or 6-week research project from nine areas or the summer course in Summer 2013, and in Summer 2014 the curriculum study option with STEM faculty was added. The features of the summer placement included type and length of activities. To be consistent, PD hours were recorded as 6 hr per day for any type of placement. For example, if a teacher joined a 4-week research project with full attendance, the PD hours would be 120 for the teacher. Attendance at PLC sessions provided the actual total hours of teachers in the monthly PLC sessions during the whole year.

Student survey

The student questionnaire was developed by the external evaluator with input from the research team from instruments previously used in other projects evaluated by the external evaluator. The survey consisted of four sets of questions, namely, students' opinion about science, what their teachers did in the classroom, what students did in the classroom, and parental support at home. An exploratory factor analysis showed three dimensions in the first set of questions and two dimensions in the other questions. After discussion between two researchers on the content of each item and a confirmatory factor analysis, the results of the survey reflected nine aspects. According to the purpose of the study, the latent traits generated from three sets of questions were used in the analyses (see Table 2). A case was considered missing when a student answered fewer than 80% of the survey questions; 7% of the sample was excluded, and the rest of the missing responses were replaced by the series mean.

Variables and data analysis procedures

To address Research Question 1, we used one-way analysis of variance (ANOVA) and a two-level hierarchical linear model (HLM) because the teachers were nested in 12 schools that might not have shared the same demographics (Raudenbush, 2004). First teacher test scores in Summer 2013 and 2014 were contrasted. Then the following model of change in teacher test scores with a series of variables was built on two time points separately:

$$Y_{tij} = \beta_{t0j} + \beta_{t1j}X_{t1ij} + \beta_{t2j}X_{t2ij} + \beta_{t3j}X_{t3ij} + r_{tij} + u_{t0j},$$

where Y_{tij} is the percentage score change of PCK; X_{t1} is a group of teacher demographic variables, including gender, experience, and highest degree; X_{t2} is PD feature, which includes summer placement type, attendance of PLC session, and total PD hours; and X_{t3} is a group of school-level demographic variables that include turnover rate, percent minority, percent poverty, and percent limited English proficiency.

To answer Research Question 3, we built another two-level HLM model of student understanding of interdisciplinary science concepts as follows:

$$Y_{sij} = \beta_{s0j} + \beta_{s1j}X_{s1ij} + \beta_{s2j}X_{s2ij} + \beta_{s3j}X_{s3ij} + r_{sij} + u_{s0j},$$

where Y_{sij} is student Rasch ability scores of student understanding of CCs; X_{s1} is a group of student demographic variables, namely, gender, race, and grade, which are treated as control variables; X_{s2} is a group of student-level variables that include self-efficacy, understanding of NOS, student-reported teacher expectation/attitude on their work and teacher support in science inquiry; and X_{s3} is a group of teacher-level predictors, which include teacher PD features, PCK results, and school demographics. School background was merged into the teacher level because of the small sample size of teachers in each school, and a pilot analysis also showed nonsignificant intracorrelations among schools.

Research Questions 2 and 4 were tested with intercorrelations and regressions by using teacher classroom practice/student self-efficacy and NOS as outcomes and teacher-level PD features and controls as variables.

Table 2. Structure of the student survey.

Question set	Factor	Items	Reliability
QS1. My opinion about science	Self-efficacy in science	Q8a, Q8b, Q8c, Q8d	.76
	Understanding of the nature of science	Q8h, Q8i, Q8k, Q8l	.61
QS2. What teachers do in classrooms	Teacher support in inquiry	Q9a, Q9d, Q9f, Q9g, Q9h	.78
	Teacher's attitude and expectation of student's work	Q9e, Q9i, Q9j, Q9l	.63
QS4. Parental support	Parental assistance	Q11a, Q11c, Q11d	.82
	Parental expectation	Q11e, Q11f	.68

Results

PD features and teacher outcomes

In Summer 2012, 44 teachers took part in science research projects and 15 teachers joined science courses. In Summer 2013, 50 teachers participated in research projects, 10 joined science courses, and 14 worked in curriculum study. Descriptive statistics for teachers' PLC attendance during the academic year and overall PCK results are shown in Table 3. The overall mean PCK scores for the Summer 2013 and 2014 cohorts were similar (53.8–55.4), which indicates that the two cohorts of teachers were comparable and that their overall level of PCK was low. However, the research group scored significantly higher than the other groups.

A significant increase in teacher attitude and expectation of student work was found from the 2013 fall semester to the 2014 spring semester (mean scores were 3.80 and 4.25 for 2013 fall and 2014 spring, respectively; $F = 11.488$, $p < .01$), whereas teacher support in inquiry and discourse remained the same. In addition, no significant intercorrelations were found between teachers' PCK scores in Summer 2013 and the other PD variables. However, PLC attendance time during the 2013–2014 academic year was positively related to teachers' PCK test scores in Summer 2014, and the regression coefficient ($B = 1.283$, $p < .05$) showed that teachers with 1 hr more than average in PLC sessions scored 1.283% higher on their PCK test. In other words, teachers who joined one more PLC session (2.5 hr) performed significantly better (approximately 3. 2 points) than those who did not, which indicates a shift from a more traditional teaching approach to a more inquiry-based approach. However, this increase was very small and thus may not be practically significant.

PD features and student understanding of CCs

Descriptive statistics are shown in Table 4. Raw test scores for student understanding of CCs were transferred into continuous Rasch scores. Variables generated from the student survey, which included self-efficacy, NOS, teacher attitude/expectation, and teacher support, were calculated by averaging the items to keep the original range of 1.00 to 5.00 (e.g., self-efficacy = [Q8a + Q8b + Q8c + Q8d] / 4). Other control variables at the student level, including gender, race, and grade, were dummy coded (e.g., for gender: 1 = female, 0 = male); thus, the

Table 3. Descriptive statistics for PLC and PCK tests.

	PLC (hr)				PCK test (%)		
	N	*M* (*SD*)	Range	Summer placement (*N*)	*N*	*M* (*SD*)	Range
2012–2013	31	7.1 (4.0)	3–18				
Summer 2013							
Science research				44	29	62.8 (23.0)	24–100
Science course				15	10	52.5 (24.1)	13–86
None				25	25	43.8 (19.8)	13–86
Total				88	64	53.8 (23.8)	13–100
2013–2014	30	5.8 (3.8)	1–13				
Summer 2014							
Science research				50	36	62.1 (23.2)	17–100
Science course				10	5	41.6 (21.2)	24–76
Curriculum study				14	10	39.8 (26.0)	13–100
None				18	18	52.9 (23.6)	13–93
Total				92	69	55.4 (24.8)	13–100

Note. PLC = professional learning community; PCK = pedagogical content knowledge.

Table 4. Descriptive statistics for students/teachers.

Variable	Code	*N*	*M* (% for dummy code)	*SD*	Range
Student level					
Rasch score	Continuous	509	−0.20	0.82	−2.33 to 3.31
Self-efficacy	Continuous	509	3.64	0.73	1.00–5.00
Understanding of NOS	Continuous	509	3.69	0.67	1.00–5.00
Teacher attitude/expectation	Continuous	509	4.04	0.61	1.00–5.00
Teacher support	Continuous	509	3.43	0.80	1.00–5.00
Gender	Categorical	509	52%		0.00–1.00
Grade 5	Categorical	509	27%		0.00–1.00
Grade 6	Categorical	509	17%		0.00–1.00
Grade 7	Categorical	509	17%		0.00–1.00
Grade 8	Categorical	509	28%		0.00–1.00
American Indian	Categorical	509	3%		0.00–1.00
Asian	Categorical	509	5%		0.00–1.00
Black	Categorical	509	31%		0.00–1.00
Hispanic	Categorical	509	17%		0.00–1.00
Multiracial	Categorical	509	11%		0.00–1.00
Teacher/school level					
Attendance hours	Continuous	23	1.35	2.67	0.00–9.00
PD hours (<75 hr)	Categorical	23	26%		0.00–1.00
PD hours (75–150 hr)	Categorical	23	30%		0.00–1.00
PD hours (>150 hr)	Categorical	23	13%		0.00–1.00
Percent disability	Continuous	23	26.70	4.17	19.00–30.00
Percent minority	Continuous	23	67.48	22.70	45.00–91.00
Grade 4 science (%)	Continuous	23	63.83	18.77	38.00–85.00
Grade 8 science (%)	Continuous	23	32.48	18.21	5.00–49.00

Note. Teacher pedagogical content knowledge results were removed from this table because fewer than half of the 23 teachers had pedagogical content knowledge records and this variable was not included in the following analyses. NOS = nature of science; PD = professional development.

means of such variables are shown as percentages of female and grade/race, accordingly. In addition, gender was distributed evenly, whereas for grade and race small sample sizes appeared in certain categories. For example, Asian students only made up 5% of the sample.

Only 23 classes were involved in the HLM analysis because only a few teachers reported the results of their students. Overall, 12 teachers participated in the ISI research, two participated in a college science and engineering course, three teachers joined curriculum study, and six teachers did not take part in any summer placement. Therefore, the type of summer placement was not considered in the HLM analysis because of the too-small sample size of classes. For teacher-level variables, PD hours was dummy coded intro three categories, namely, less than 75 hr, 75–150 hr, and more than 150 hr. Attendance in PLC kept its original forms of continuous values. The four school demographic variables represented average percentages of disabled students, minority, and Grade 4 and Grade 8 science performance for the five elementary/middle schools .

Results of ANOVA (*t* tests for gender) are shown in Table 5. Female students' average Rasch ability score was significantly higher than male students' (t = 4.464, p < .05); the scores increased gradually from Grade 4 to Grade 8, and the differences among groups were significant (F = 5.691, p < .001). The post hoc test showed that students in elementary school (Grades 4–6) had similar ability, and a significant achievement difference was found between elementary school and middle school (Grades 7 and 8). In terms of race, Black students scored significantly lower than students of other races, but there was no significant difference among the rest.

Table 5. Results of *t* tests and analysis of variance for control variables.

Control variable	Category	*N*	Rasch score, *M* (*SD*)	Min	Max
Gender (*t* = 4.464*)	Male (0)	246	−.275 (.841)	−2.33	3.31
	Female (1)	263	−.123 (.789)	−2.33	2.79
	Total	509			
Grade (*F* = 5.691***)	Grade 4	61	−.428 (.689)	−2.23	1.02
	Grade 5	136	−.324 (.684)	−2.33	1.32
	Grade 6	85	−.304 (.735)	−2.33	1.43
	Grade 7	86	−.102 (.805)	−2.33	1.32
	Grade 8	141	.033 (.972)	−2.33	3.31
	Total	509			
Race (*F* = 7.404***)	Black	157	−.508 (.767)	−2.33	1.32
	American Indian or Alaska Native	15	−.144 (.583)	−1.04	.91
	White	171	−.085 (.876)	−2.33	3.31
	Hispanic	86	−.081 (.699)	−2.33	1.32
	Multiracial	57	.023 (.775)	−1.46	2.08
	Asian	23	0.952 (.791)	−1.46	1.55
	Total	509			

*$p < .05$. ***$p < .001$.

Based on these results, student grade was combined into a new variable that contained two categories, namely, elementary and middle school. Race was recoded into Black, White/Hispanic, and other races (including Native American or Alaska Native, Asian, and multiracial in this case). The recoded control variables were used in the following HLM analyses to increase accuracy. The overall correlation matrix of student-level variables is shown in Table 6. All variables were positively correlated with student Rasch score, and no collinearity was found between the predictors; thus, further analyses were suggested.

PD features, teacher practices, and students' understanding of NOS and self-efficacy

Among student-level predictors (see Table 7, Model 2), student self-efficacy, understanding of science, and teacher support in inquiry were positively related to student Rasch scores ($B = 0.17$, $p < .01$; $B = 0.13$, $p < .05$; and $B = 0.16$, $p < .05$, respectively) when gender, race, and grade were held constant. Students with 1 point higher than the grand mean in self-efficacy/NOS/teacher support scored 0.17/0.13/0.16 higher in their Rasch scores on average. Teacher attitude/expectation toward student work was not significant. The variables explained 16% of the total variance in student ability.

The fully unconditional model (see Table 7, Model 1) showed significant variance (21%) between classrooms ($u_0 = 0.142$, $p < .001$). Because random effects of student

Table 6. Correlation matrix of student-level variables.

Variable	1	2	3	4	5	6	7	8
1. Rasch score	—							
2. Gender	.093*	—						
3. Grade	.196**	.037	—					
4. Race	.239**	−.091*	−.042	—				
5. Self-efficacy	.198**	−.001	−.082	.061	—			
6. Nature of science	.241**	.000	.111*	.094*	.302**	—		
7. Teacher support	.139**	.034	.097*	.057	.244**	.300**	—	
8. Teacher attitude	.200**	.050	−.071	.070	.294**	.268**	.460**	—

*$p < .05$. **$p < .01$.

Table 7. Results of hierarchical linear modeling analyses.

	Model 1	Model 2: Fixed effects *B* (*SE*)	Model 3: Fixed effects *B* (*SE*)
Student level			
Self-efficacy		0.17** (0.05)	0.17** (0.05)
NOS		0.13* (0.05)	0.12* (0.05)
Teacher support		0.16* (0.06)	0.16* (0.06)
Teacher level			
Attendance			−0.06 (0.04)
PD hours			
<75			−0.25 (0.17)
75–150			0.02 (0.15)
>150			0.71* (0.25)
u_0	0.142	0.086	0.046
r	.526	.476	.476
Pseudo-R^2	.00	.16	.22

Note. NOS = nature of science; PD = professional development.
$^*p < .05$. $^{**}p < .01$.

variables were not the focus of this study and none of the results were significant, they are not shown in this section. After adding teacher-level predictors of PD and school demographics (see Table 7, Model 3), we found that the coefficients of student-level variables remained stable. Significant difference was found among different groups of PD hours. Students whose teachers had more than 150 hr of PD scored significantly higher than those whose teachers had no PD ($B = 0.71$, $p < .05$), and the average difference in Rasch ability was 0.71 points. Furthermore, ANOVA showed no difference among the teachers in the other three groups of PD hours. Thus, the variable was recombined into two categories: teacher PD hours more than 150 hr and less than 150 hr. The teacher-level variables explained another 6% of the variance in student Rasch scores.

Possible mediation effects of PD features and student learning outcomes

Possible mediation effects between teacher PD hours and student understanding of CCs were tested through simple regression using PD hours as the independent variable and the four significant student-level variables as outcomes. Teacher PD hours was merged into the student level in the analyses. The recoded variable of PD hours showed a significant relationship with student understanding of CCs ($B = 0.51$, $p < .001$). Students whose teachers had more than 150 hr of PD scored 0.51 higher than those whose teachers had less than 150 hr of PD. None of the variables at the student level were significantly correlated with teacher PD hours. Furthermore, student understanding of NOS was marginally significant ($B = 0.25$, $p < .10$), which indicates a possible positive association between the two variables. The difference in student understanding of NOS between the two groups was 0.25 points on average and favored the group with PD hours more than 150 hr. Therefore, a possible mediation effect exists between PD hours and student understanding of CCs through student understanding of NOS. Further analyses are needed to confirm the effect.

Discussion

PD features and teachers' PCK results

The teacher PCK results should be interpreted with caution because the tests of teacher PCK only reflected a few components, including SMK, knowledge of leaners, orientation toward teaching science, and knowledge of instructional strategies. These components of PCK were found to be related not to total PD hours but to the ISI research experience. The ISI research groups, both the Summer 2013 and 2014 cohorts, scored significantly higher. The reasons for this may be that ISI research provided teachers with authentic experience in doing science through inquiry. For one thing, teachers' knowledge of ISI was improved during the process, and a solid knowledge base was required for teachers to adopt inquiry instruction (Abell, 2007). For another thing, teachers' own experience in ISI might have changed their attitudes toward inquiry and inquiry instruction. According to van Aalderen-Smeets and van der Molen (2015), teachers with more positive attitudes, such as higher joy and self-efficacy and lower anxiety, were more likely to change their behavior toward teaching strategies of inquiry.

Furthermore, attendance at PLC sessions was positively related to teachers' PCK test results. The PLC sessions were designed to improve ISI implementation by directly targeting different components of PCK, as mentioned previously. Each session aimed to address one certain issue in the implementation of ISI in classrooms, such as instructional strategy of ISI. The PLC sessions also provided teachers with opportunities to improve their understanding of NOS and attitudes toward inquiry and to share experiences with ISI implementation. Thus, teachers who frequently participated in PLC sessions were more likely to choose inquiry-oriented instruction.

PD features and student-reported teacher classroom practice

Teachers' support in science inquiry may be difficult to change compared to their attitude/expectation; no relationship was found between PD features and the two variables of teacher practice. These results are consistent with previous studies of teacher change in classroom practices (Brickhouse, 1990; Garet et al., 2001; Savasci & Berlin, 2012; Windschitl, 2003). The reasons for not changing teacher classroom practices were not the focus of this study but were the focus of another multiyear ethnographic study (E. Smith, 2014). E. Smith found that constraining factors, including (a) coherence between teacher beliefs about translating ISI research experiences and students' ability to do inquiry, (b) exam-driven instruction and curriculum, (c) misconception of students' overall academic weakness, and (d) lack of resources, inhibited teachers from implementing ISI in their teaching. Therefore, the teachers decided not to change their classroom practice by considering the tradeoffs.

PD intervention and students' understanding of interdisciplinary science

The relationships between Rasch scores of student understanding of CCs and student-level variables are consistent with previous studies. Gender difference (V. E. Lee & Burkam, 1996), racial gap (Catsambis, 1995), and student learning growth (Liu, 2007) in science achievement are significant, and they were well controlled to eliminate bias in other analyses in this study. Student self-efficacy, understanding of NOS, teacher attitude/expectation of work, and teacher support in science inquiry were all positively correlated, which indicates an internal consistency in the survey results. Furthermore, student self-efficacy and understanding of NOS were positively related to students' understanding of interdisciplinary science. The results are consistent with previous studies of students' self-efficacy and their science achievement, and they also provide empirical evidence for the effect of NOS on student learning outcomes (Baker & White, 2003; Lederman, 1992; McComas, Clough, & Almazroa, 1998; Pajares, Britner, & Valiante, 2000).

Specific research on how teacher expectation/attitude toward student work and teacher support in science inquiry influence the science learning outcomes of students in elementary/ middle school is rare. In a study on a high school classroom environment, authors found that teacher support, order and organization, and innovative teaching strategies demonstrate a positive relationship with student attitudes toward science (Myers & Fouts, 1992). Fogleman and colleagues (2011) conducted HLM analyses of relationships between teacher curricular adaptations and student learning outcomes in a science unit. They found that students who completed investigations by themselves had higher learning gains than their peers who observed their teacher completing the investigations. The positive correlations in this study show a similar pattern because teacher support in inquiry reflects how teachers help students to complete tasks by themselves. Given the latent trait measured by the instrument, which is understanding of CCs, the associations with two teacher variables are reasonable. Science inquiry, though difficult to implement, will improve student conceptual change in science knowledge (Cuevas, Lee, Hart, & Deaktor, 2005; Duschl & Osborne, 2002; Keys & Bryan, 2001; Wallace & Kang, 2004). This study provides evidence of the positive relationship between teacher support in science inquiry and student understanding in interdisciplinary science.

In HLM analyses, PD more than 150 hr was the only significant variable at the teacher level; the associations of student- and teacher-level variables were independent. These results are consistent with previous studies on the duration of effective PD. The time duration for effectiveness varies according to the purpose of the PD (Banilower et al., 2007; Supovitz & Turner, 2000). However, the higher performance of students may also be due to the teacher selection process. Teacher beliefs and attitude have been proved to have a direct impact on student achievement, as mentioned previously. In other words, teachers who join longer PD sessions are likely to have a more positive attitude and be passionate in learning and developing. Therefore, the influence embeds into their everyday instruction and eventually impacts student achievement. Furthermore, teachers with PD hours more than 150 hr were the coordinating teachers in their respective school buildings. Perhaps this extra responsibility may also have reflected their positive attitudes. However, background information on the teachers, such as their beliefs and attitudes, was not available in this study. Further studies should use a more controlled sample to study this possible effect.

Through the analyses in the study, student understanding of NOS was found to possibly mediate the relationship between PD hours and interdisciplinary science understanding. Students whose teachers took more than 150 hr of PD had higher self-perceived understanding of NOS compared with the other groups, and therefore they also had a higher Rasch ability of understanding of CCs. The reason for this might be that NOS, particularly the nature of interdisciplinary science, was experienced by the teachers in their own ISI research through summer and also through reflection on ISI research experience in the form of a research poster presentation and in PLC sessions on the nature of interdisciplinary science.

The results indicate that the PD program and the measure of student learning outcome might not be perfectly aligned. More detailed and specific studies are required to explore the relations in the aforementioned model of the effectiveness of PD. Further research design should focus on the alignment of the purpose of the PD program, evaluation of teacher development, reflection of teacher change in knowledge and practices, student change in attitude/beliefs, and measurement of student learning outcomes to provide empirical evidence of the effectiveness of the PD program.

Conclusions and implications

To conclude, the relationships between PD and teacher PCK assessment/classroom practice are sensitive to the content and duration of the PD program. Teacher PCK correlates positively with participation in PD of ISI research and PLC sessions that targets methods of instruction. However, teacher classroom practices in terms of support in science inquiry and attitude/expectation of student work show no relationship with the PD intervention. Furthermore, overall PD hours relate positively to student understanding of CCs, and a significant increase is found at the point of 150 hr per year, thus supporting the idea that a certain amount of PD is required to show effects on student achievement. Of course, this conclusion assumes that the PD is of high quality and is highly relevant to the participating teachers. Moreover, the relationship between PD and student understanding of CCs could possibly be mediated by student understanding of NOS, though how this mediation happens remains unclear.

This study broadens the knowledge of PD and teacher/student achievement in science teaching and learning. The statistical results of the study provide empirical evidence of the effectiveness of PD programs in terms of coherence and duration. Also, the study sheds light on how the effects of PD could ultimately benefit student learning outcomes. According to the results, a certain amount of PD every academic year is needed to positively affect student understanding of interdisciplinary science.

Findings from this study can inform science teacher PD programs. First, for any PD program with a well-defined purpose, the duration of PD is essential to the overall effects. Thus, teacher PD programs that are intense and of a short duration should be viewed with caution. Second, measurements of PD outcomes should be specific, aligned with the purpose, and allow a period of time for the PD to exhibit effectiveness. For example, assessment of teacher achievement after joining a research project must start with something directly related to the project. Third, the length of the PD intervention is found to be effective in improving student understanding of NOS and thereby increasing understanding of interdisciplinary science. Therefore, it is suggested that teachers consistently attend PD programs and incorporate NOS into their classrooms through implementation of ISI.

Further research is needed to identify more contributing factors in the relationships among PD features, student learning outcomes, student beliefs/attitudes, teacher beliefs/attitudes, and classroom practices. A holistic perspective of these relationships is needed to expand knowledge of teacher PD and inform future PD design.

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Appendix A

Item Description for All Latent Variables

Table A1. Item description for all latent variables.

Item	Description
Self-efficacy in learning science	
Q8a	I like science.
Q8b	I am good at science.
Q8c	I would keep on taking science classes even if I did not have to.
Q8d	I understand most of what goes on in science.
Understanding of the nature of science	
Q8h	Scientists sometimes disagree about scientific knowledge.
Q8i	All scientists do not follow the same step-by-step method to do science.
Q8k	Science ideas or hypotheses must be supported by evidence.
Q8l	Scientific theories can change when new evidence or a new explanation becomes available.
Inquiry teaching	
Q9a	Arranges the classroom so students can have discussion
Q9d	Encourages me to ask questions
Q9f	Encourages me to explain my ideas to other students
Q9g	Encourage me to consider different scientific explanations
Q9h	Provides time for me to discuss science ideas with other students
Teacher expectation	
Q9e	Let me work at my own pace
Q9i	Checked that I have completed my assignments
Q9j	Provides meaningful and challenging assignments
Q9l	Expects me to do well
Parental expectation	
Q11e	Expects me to do well in science
Q11f	Expects me to go to college
Parental assistance	
Q11a	Makes me do my science homework
Q11c	Helps me with my science homework
Q11d	Helps me work on my science projects

Appendix B

Item Description for Instrument of Interdisciplinary Science

Table B1. Item description for instrument of interdisciplinary science.

Source	Item	Crosscutting concepts in the context of disciplinary core ideas
SASKS	1, 2 (two tiered)	P in the context of biodiversity
	3, 4 (two tiered)	C&E in the context of the moon phase
	5, 6 (grouped)	S, P&Q and E&M in the context of experiment design and data representation
	7, 8 (two tiered)	S, P&Q and C&E in the context of Archimedes' principle
DIT	9	P and S, P&Q in the context of properties of materials
	10	P and S, P&Q in the context of measuring quantity
OAA	11	C&E and E&M in the context of conduction
	12	C&E and E&M in the context of energy flow
	13	S&F in the context of biodiversity
	14	S&F in the context of plant reproduction
	15	S&F and C&E in the context of ecological system
	16, 17, 18 (grouped)	S&SM in the context of experimental design, repetition, and modification
	19	C&E and E&M in the context of energy transfer
	20	C&E in the context of plant reproduction

Note. According to the Next Generation Science Standards, P = pattern; C&E = cause and effect; S, P&Q = scale, proportion, and quantity; E&M = energy and matter; S&F = structure and function; S&SM = systems and system model. SASKS = Science Attitudes, Skills, & Knowledge Survey; DIT = Discovery Inquiry Test; OAA = Ohio Achievement Tests.