Insights on How to Shape Teacher Learning Policy: The Role of Teacher Content Knowledge in Explaining Differential Effects of Professional Development

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Abstract: In the US, many federal, state and local school improvement policies rely on teacher professional development (PD) to foster classroom change. Past research suggests PD that has a content focus is the most effective, but that even content-focused PD varies in its effectiveness. Through in-depth interviews of teachers participating in a middle school science PD randomized

control trial in the US, we find that what teachers learn in PD varies significantly based on their prior knowledge and experience. This paper explores several hypotheses about how content knowledge and teacher learning interact. We conclude that the next step toward improving teacher PD is to calibrate learning opportunities to teachers' prior knowledge.

Keywords: learning policy; teacher professional development; teacher learning; content knowledge; pedagogical content knowledge

Ideas sobre cómo dar forma a la política de aprendizaje de los maestros: El papel del conocimiento del contenido en la explicación de los efectos diferenciales de desarrollo profesional

Resumen: En los Estados Unidos, muchas de las reglas y políticas en las escuelas locales, estatales y federales se basan en el desarrollo profesional (DP) para promover cambios positivos en los salones. Investigaciones anteriores han sugerido que el DP se ha centrado en el contenido que es el más eficaz, pero incluso existe el DP centrado en un contenido que suele variar en su efectividad. A través de entrevistas con profesores que participaron en un estudio de control aleatorio de DP en una escuela secundaria de ciencia en los EE.UU., descubrimos que lo que los maestros aprenden en el DP varía significativamente en función a sus conocimientos y experiencia previa. Este artículo explora algunas hipótesis acerca de cómo interactúan el conocimiento del contenido y los maestros de aprendizaje. Llegamos a la conclusión de que el siguiente paso para mejorar el DP de los maestros es crear oportunidades de aprendizaje de conocimiento previo de los profesores.

Palabras clave: política de aprendizaje; el desarrollo profesional de los maestros; maestros de aprendizaje; el conocimiento del contenido; conocimiento didáctico del contenido

Uma visão sobre como dar forma na política de aprendizagem de professores: O papel do professor em conhecimento de conteúdo em explicar efeitos diferenciais de desenvolvimento profissional

Resumo: Nos Estados Unidos, muitas políticas de melhorias nas escolas municipais, estaduais e federais dependem de desenvolvimento profissional de professores (DP) para promover a mudança de sala de aula. Pesquisas anteriores sugerem DP que tem um foco de conteúdo é o mais eficaz, mas que mesmo DP focado em um conteúdo varia em sua eficácia. Através de entrevistas com professores que participam de uma tentativa de controle aleatório de DP em uma escola de ciências de ensino médio nos EUA, achamos que o que professores aprendem em DP varia significativamente com base no seu conhecimento e experiência prévia. Este artigo explora algumas hipóteses sobre como o conhecimento de conteúdo e aprendizagem de professores interagem. Concluímos que o próximo passo para melhorar DP de professores é calibrar oportunidades de aprendizagem ao conhecimento prévio dos professores.

Palavras-chave: política de aprendizagem; desenvolvimento profissional de professores; aprendizagem de professores; conhecimento do conteúdo; conhecimento pedagógico do conteúdo

Introduction

Teacher learning is a central component of many school reform policies at the national, state, and local levels in the United States. Standards-based reform, comprehensive school reform, accountability systems such as those developed under educational policies such as No Child Left Behind, and curriculum reforms like the recent Common Core State Standards (CCSS) in the United States are no exception. There are already multiple state efforts focused on designing and developing professional development (PD) to help teachers build their instructional skills and content

knowledge (CK) in order to improve their teaching in ways that respond to the CCSS. For example, the role of PD in supporting teachers is especially emphasized in recent science reforms, including *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* (National Research Council, 2012) and the Next Generation Science Standards (NGSS Lead States, 2013). In other words, teacher CK and pedagogical skills play important roles in the success of the implementation of many reforms and, as such, we need to have a better understanding of the policies and practices related to teacher learning.

What do we know about building teachers' CK and instructional skills to improve student learning? Previous research supports several general principles that are important for the effectiveness of PD. First, building teachers' CK in meaningful ways requires sustained, content-focused PD that is embedded in teachers' work lives and that allows for practice, discussion, and feedback (Ball & Cohen, 1999; Garet, Birman, Porter, Yoon, & Desimone, 2001; Ingvarson, Meiers, & Beavis, 2005; Little, 1982, Loucks-Horsley, Hewson, Love, & Stiles, 1998). Second, translating CK into improved instructional strategies is not automatic; the process works through various mechanisms including increased confidence, willingness to ask higher level questions, proclivity to experiment, ability to identify student mistakes, and many others (e.g., Bitan-Friedlander, Dreyfus, & Milgrom, 2004; Hill, Rowan, & Ball, 2005; Lee & Luft, 2008; Maskit, 2011; Parker & Heywood, 2000). Third, teachers vary considerably in what they learn and how they translate that knowledge into practice, and we do not know as much as we should about why this variation occurs. That is, given a common high-quality PD experience, there is considerable variation in the extent to which teachers increase their knowledge, implement new practices with high fidelity, understand the changes, and elicit effects on student achievement (e.g., Domitrovich et al., 2009; Garet et al., 2010; Gowlett et al., 2015; Penuel, Fishman, Yamaguchi, & Gallagher, 2007). In order to understand how to better shape and target PD so that it is effective for all teachers, it is important that we have a fuller understanding of this variation in PD effectiveness.

Our study explores the differential effectiveness of teacher PD through teachers' reflections on their learning. We seek to unpack why so-called "high-quality" PD—PD that is focused on content, provides active learning opportunities, is coherent with the teacher's curriculum and other school efforts, is of sufficient duration (e.g., lasts 20 hours or more over a span of several months), and provides opportunities for teachers to interact with others (see Desimone, 2009; Yoon et al., 2007)—has such varying effects on teachers. Although a myriad of factors may explain this variation, including context, organization, personal characteristics, beliefs, leadership, and curriculum, we focus here on teacher CK. We ground our work in the strong research base linking CK to the effectiveness of teachers' instruction (Cohen, McLaughlin, & Talbert, 1993; Hill, Ball, & Schilling, 2008) and the substantial work investigating the interaction of content and pedagogy in teacher training (Ball, 2000; Boyd, Grossman, Lankford, Loeb, & Wyckoff, 2009; Darling-Hammond, 1997; Grossman, 1990; Putnam & Borko, 1997).

The analysis presented here focuses on the following broad question related to explaining variation in teacher learning and effects from high-quality PD: *How does teacher CK moderate the effects of PD on teachers, and how does the nature of the PD—whether it is focused on content only or content and pedagogy—influence this relationship?* We focus on differences between two groups of teachers: those with strong middle school science CK, and those with weak middle school science CK. Although we describe variation within these two groups, in this study our primary focus is on between-group variation.

PD and Teacher Knowledge and Practice

Central in widely held theories of action for PD is the notion that teachers' learning experiences, in combination with a host of contextual and personal factors, drive changes in what teachers know and do (Borko, 2004; Desimone, 2009; Supovitz, 2001). A collective understanding of key features of PD that are most likely to lead to changes in teacher knowledge and instructional practice has emerged: prioritizing an emphasis on the content of teachers' instruction, the collective participation of teachers from the same school, an extended focus on a particular PD initiative, and a close connection to teachers' day-to-day work of teaching, among other features (Garet et al., 2001). Translating PD content and implementing new instructional practices so that they can be used effectively in the classroom is a complex process. We know that such translation is moderated by teachers' prior knowledge, beliefs, and practices, even if we do not know precisely how.

Cohen (1990) argued that imperfect implementation of an intervention is related to a lack of opportunities for observation and feedback, too little assistance in integrating previous practices with new practices, and insufficient understanding of the subject and the goals of the reform. Borko and Putnam built on Cohen's work by emphasizing that PD learning experiences need to help teachers build new knowledge and beliefs in order to be effective (Borko & Putnam, 1996). Further, Borko and Putnam provided us with an overview of the complexity and importance of social interactions in teacher learning (Borko, 2004; Putnam & Borko, 1997). Their work emphasized the importance of considering teacher context and classroom experiences in shaping policies and practices to promote teacher learning.

Related research efforts over the past 3 decades have aimed to uncover the particular nature of knowledge used in teaching in order to improve teacher effectiveness. These lines of work have fostered a general acceptance of the notion that general CK in a subject like science, such as might be imparted via a university textbook, is distinct from pedagogical content knowledge (PCK), or the specialized knowledge necessary to convey content effectively to students. Furthermore, PCK is theorized to be multifaceted, incorporating aspects of knowledge such as knowing appropriate models to illustrate concepts and understanding how students learn in a particular content area (Shulman, 1986). Work by Ball and her colleagues has focused on further defining the particular domains of knowledge for teaching, and these researchers have provided empirical evidence of the role of a profound understanding of instructional content in enabling teachers to instruct in ways that support student learning (Ball, 1990, 1991; Ball & Rowan, 2004; Ball, Lubienski, & Mewborn, 2001). Their arguments make clear that this type of knowledge is not simple or straightforward to attain. They identified links between CK for teaching and the use of certain instructional strategies that elicit student learning, such as identifying student mistakes and engaging in deeper level conversations (Ball, Thames, & Phelps, 2008; Hill, Rowan, & Ball, 2005).

These general principles have been shown to apply across content areas, including science. While teacher knowledge in science has not received as much attention as in mathematics (see Diamond, Maerten-Rivera, Rohrer, & Lee, 2014), research has established a link between teachers' knowledge of science and their students' science achievement (e.g., Fleer, 2009; Shallcross, Spink, Stephenson, & Warwick, 2002; Supovitz & Turner, 2000). As in mathematics, there seems to be a consensus that elementary and middle school teachers on average do not have the strong science knowledge needed to foster 21st-century science learning (e.g., Jüttner, Boone, Park, & Neuhaus, 2013; Nowicki, Sullivan-Watts, Shim, Young, & Pockalny, 2013), but that when they do, they are better able to foster deep and meaningful student learning across multiple science domains (Diamond et al., 2014).

These ideas stressing the important links among teacher knowledge, instruction, and student learning have been the focus of many conceptual and empirical expositions across different subjects, including science (e.g., Diamond et al., 2014; Maerten-Rivera, Ahn, Lanier, Diaz, & Lee, in press; Schmidt, McKnight, & Raizen, 1997), mathematics (e.g., Borko et al., 1992), and English (Grossman, 1989).

Toward an Understanding of PD Impacts

The work of these researchers has guided PD designers and experimentalists in testing PD interventions in randomized controlled trials (RCTs) in order to understand how to better develop effective PD as part of district and school improvement policies. The links to this foundational work are obvious in the consistent focus on content-focused PD with various features that the previous work has extolled as "high-quality" and necessary to elicit teacher change, such as practice opportunities, links to the classroom, sustained learning experiences, and collaborations with other teachers (Borman, Gamoran, & Bowdon, 2008; Garet et al., 2008, 2010; Penuel et al., 2007).

The effects of these experiments are mixed. Some show positive effects on increased knowledge of both teachers and students (Heller, Daeler, Wong, Shinohara, & Miratrix, 2012), demonstrating, for example, that PD in science can improve both teacher and student learning (Maerten-Rivera, Huggins, & Adamson, 2013). Many have positive effects on teachers but not on students (Garet et al., 2010). Some have effects on particular groups of students but fail to show average effects (e.g., Borman, Gamoran, & Bowdon, 2008). Still others show no differences among treatment and control teachers, even with an intensive high-quality PD experience (e.g., Davidson, Fields, & Yang, 2009). Measurement, design, power, and other technical issues aside, how might we interpret findings from these rigorous, causal studies that do not demonstrate strong links between PD participation and knowledge and practice change that we might expect, given findings from the foundational work establishing the PD–knowledge–practice links? A careful examination of recent rigorous PD experiments shows repeatedly that the same PD often results in variation in effects on teachers and students based on teacher characteristics such as novice status and, most often, CK (Davidson et al., 2009; Santagata, Kersting, Givvin, & Stigler, 2012; Yoon, Liu, & Goh, 2010). Thus, while considerable evidence suggests variation in teacher response to PD, there is little focus on understanding how and why teacher differences result in variation in outcomes (for recent consideration of variation of within-school policy take up, see Gowlett et al., 2015).

A Middle School Science Study Provides an Opportunity to Investigate

To shed light on this question about the differential effectiveness of PD, we conducted an in-depth interview study of a subset of teachers participating in a three-armed RCT focused on middle school science teachers and their students. The study provided an opportunity to explore teacher experiences in a high-quality PD program and their resulting reflections on their knowledge and instructional growth. We have quantitative assessments of teachers' CK and classroom implementation as well as qualitative interview data on their PD experiences and classroom implementation. This mix of quantitative and qualitative data enables us to explore the links among the nature of PD, teacher CK, and the perceived effects of PD on teacher learning and instruction.

We seek to help explain how teacher CK moderates teacher learning and responses to PD as a way to gain a better understanding of how to effectively shape and target PD policies and programs. We describe trends in the relationship between teacher CK and teachers' views about

what they learn in PD, and how this differs depending on the nature of the PD—whether it focuses purely on subject matter content or includes both content and pedagogical strategies.

Theory of Action

In Figure 1, we present our theory of action, which we apply here to teacher CK, although it can be applied to other teacher characteristics. We recognize that our theory of action includes only some of the important and complex relationships that stem from high-quality PD; we do not intend the model to be all encompassing. Instead, we use our model to help frame an understanding of what emerged from our interviews regarding relationships among prior CK and CK gained through the PD, PCK, and affective outcomes (i.e., confidence, risk taking, etc.), each of which have been shown to be related to student achievement (e.g., Buczynski & Hansen, 2010; Hill, Rowan, & Ball, 2005; Ingvarson et al., 2005; Penuel et al., 2007). Additionally, we note that this theory of action can be used for various methods of measuring these relationships—including teacher reflections (as done here) or quantitative assessments of learning, for example.

In Figure 1, we represent the CK, PCK, and affective outcomes gained through PD as separate boxes. Within each of those boxes there are two arrow lines—a dashed arrow line to represent someone with strong prior CK and a solid arrow line to represent someone with weak prior CK. The arrow lines are of varying height to represent what is gained from the high-quality professional development.

We plot potential gains (among many) in order to illustrate our conceptualization. The first one is a potential gain for a teacher with strong prior CK, represented by the dashed arrow line. Because the teacher already has strong CK prior to the PD, it is likely that the teacher will not gain or perceive a large amount of additional CK, indicated by a short dashed line; she may, however, notice an increase in her level of PCK and/or confidence in teaching. In other words, high-quality PD has the potential to provide teachers with a variety of benefits; however, what the teachers learn likely depends on their initial knowledge level.

Another example is a teacher with weak prior CK, represented by the solid arrow lines. This teacher has more potential to increase her CK. However, CK is not the only possible benefit from the PD. If a teacher has weaknesses in both CK and PCK, then the teacher may notice a little learning from both or she may focus her attention on CK and note an increase in CK. In other words, if there are multiple knowledge gaps to fill, the teacher could fill one gap or partially fill both gaps. We intend the model to reflect that teachers' change in CK, PCK, and affective characteristics depends on interactions between the quality and content of the PD with the teachers' prior knowledge.
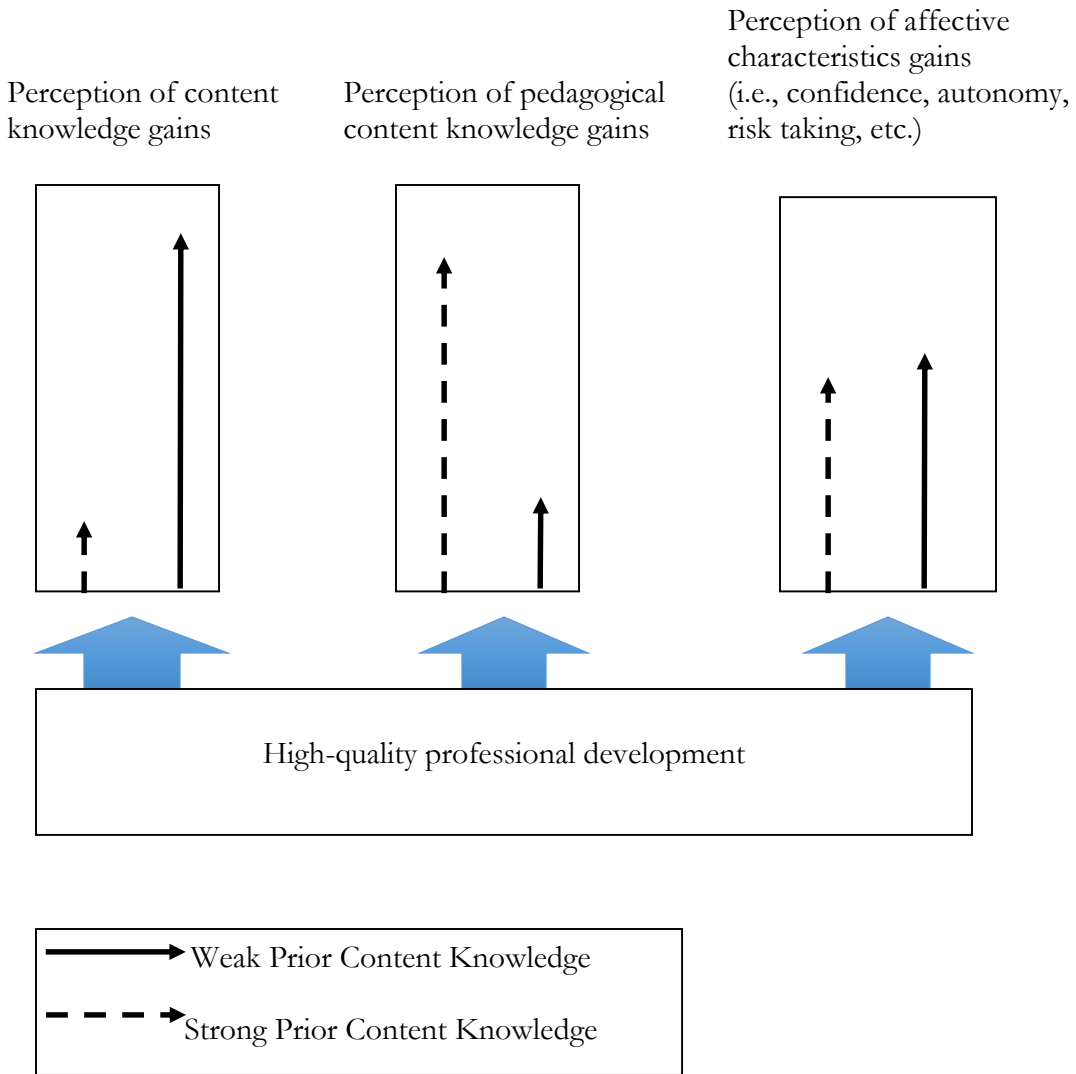
Figure 1. Theory of Action of the Potential Role of Content Knowledge in Differential Learning from Professional Development

Description of the Intervention Study

The broader study that served as the backdrop for our investigation was a three-armed RCT. It tested two conditions against a control group. The two main hypotheses of the study were (a) student achievement in middle school science will increase when teacher content knowledge increases, and (b) student achievement in middle school science will increase to a greater extent when teachers are taught key cognitive science principles and how to use them (Bransford & Schwartz, 1999; Chi, 2005; Hegarty, Kriz, & Cate, 2003 as cited in Merlino et al., 2008). The intervention targeted three middle school science units—biological, geological, and physical sciences. The intervention lasted for 3 years, occurring in phases. The first year focused only on the biological science unit for 7th-grade teachers. In the second year we added the geological science unit and the physical science unit for 8th-grade teachers. The third year included only the geological science and physical science units. Teachers could be involved in the study for a total of 3 years, teaching each unit twice.

Content-only Intervention

In this first condition, teachers participated in a high-quality PD that exposed them to deep and advanced content related to the topics covered in each unit. The PD was provided by science museum professionals, university professors, and researchers. The teachers also received a binder of content-specific material related to topics covered in the unit (Massey, Cleland, & Mandel, 2013). For the geology unit that is the focus of this study, content covered topics such as rock classifications, plate tectonics, and volcanoes. The PD was pure content knowledge; the teachers were not given any explicit guidance as to how to incorporate the content knowledge into their courses. We refer to teachers who participated in the content-only intervention as being part of the content arm of the study.

Content-plus-pedagogy Intervention

In the second condition, which we refer to as the cognitive science, or content-plus-pedagogy, arm of the study, teachers received PD that taught them the tenets of four cognitive science principles—analytic reasoning (contrasting cases), diagrammatic reasoning (visualizations), the role of background knowledge (student misconceptions), and understanding and long-term retention (spaced testing). They also received explicit instruction and materials on how to integrate these principles into their classroom instruction, including a detailed "Cognitive Science Manual" (CSM), prepared by our research team, which provided guidelines, lessons, warm-ups, and assessments for each of the three intervention units. Because the CSM was designed to be used in place of the district's planning guide for each of the three units, the topics in the CSM aligned with the district's guide but were modified to integrate each of the four cognitive science principles. Each of these principles is grounded in the literature and described in the following sections based on the research that was conducted for the funding proposal (Spencer, Desimone, & McMaken, 2011).

Analytic reasoning using contrasting cases. Analytic reasoning using contrasting cases is based on the work of Bransford and Schwartz (Bransford & Schwartz, 1999; Schwartz & Bransford, 1998). Using contrasting cases helps students learn new material and concepts (Bransford & Schwartz, 1999; Gentner, Loewenstein, & Thompson, 2003; Kurtz, Miao, & Gentner, 2001; Schwartz & Bransford, 1998). For example, contrasting cases helps the students identify important

features, make inferences, explain their own reasoning, understand the underlying concepts, and prepare for future learning (Chi, 2000; Chi, Bassok, Lewis, Reimann, & Glaser, 1989; Chi, De Leeuw, Chiu, & LaVancher, 1994). The intervention materials asked the teachers to use contrasting cases at the beginning of the lesson and to have their students read about and contrast two concepts (Merlino et al., 2008). In the geology unit, one contrasting case involved geological time represented as a table and as a football field. Students were asked to complete a chart describing how each representation depicts when Earth was formed and the length of particular eras. After the students spent time reasoning about the similarities and differences of the two representations, the teacher led a discussion about the two concepts. Overall, the contrasting case activities usually took one to two days (Yang, Porter, Massey, & Merlino, 2016).

Diagrammatic reasoning using visualizations. The visualizations component was based on research indicating that middle school students often have trouble decoding graphs, charts, and other visualizations (e.g., Hegarty et al., 2003) (Merlino et al., 2008), and it was designed to improve student spatial reasoning skills. The intervention provided teachers with strategies for teaching students how to understand visualizations, such as teaching students how to explicitly identify key ideas represented by a visualization, and it emphasized the importance of decoding visualizations on a regular basis rather than waiting for students to ask about them.

Student background knowledge. Students bring with them a combination of knowledge from informal learning and limited formal science education, and often, informal learning leads to misconceptions (Chi, 2005; Vosniadou, Skopeliti, & Ikospentaki, 2004). Our decision to include this component emanated from research suggesting that in science a set of common misconceptions often go uncorrected (Merlino et al., 2008). However, students do not necessarily hold the same misconceptions about a concept, making it difficult for teachers to identify when students have misconceptions (Minstrell, 2001). The intervention offered teachers strategies for addressing these misconceptions directly (Merlino et al., 2008). For example, students may believe that humans and dinosaurs lived on Earth at the same time. Using various representations of geological time, such as those from the contrasting cases described above, a teacher can help students recognize that the timing of dinosaurs did not overlap with humans.

Long-term retention through spaced testing. Testing students on material at spaced intervals helps them retain that information more so than simply reviewing the material, because testing the students at spaced intervals requires students to repeatedly retrieve the relevant information (Roediger & Karpicke, 2006). The cognitive science intervention provided teachers with quizzes for their students and indicated the particular days on which to give the quizzes. Not only did these quizzes include the most recently covered content, but they also included content from earlier in the unit. For example, the geology unit began by covering the geological timescale, and throughout the unit, the quizzes asked questions about the geological timescale, requiring students to retrieve that information from earlier classes and quizzes.

The Control Group

Teachers in the control condition engaged in business as usual—no alternative PD was offered to those teachers at the time of the study. However, as an incentive for participation, we offered to provide the intervention materials and accompanying PD at the end of the study to all teachers in the district who wanted them.

Structure of the PD

To reduce confounding, we designed both the content-only and the cognitive science PD to have the same structure, duration, and core features despite the content arm's focus on content only and the cognitive science arm's focus on pedagogy and curricular materials. For both arms, we provided a 2.5-day (18 hour) summer PD and four 2-hour professional learning community (PLC) sessions during the school year for 2 years, for a total of 34 hours of PD over 6 months for each unit.[1] The summer PD in both conditions included a mix of lectures, laboratories, interactive discussions, and observations with feedback. The PLC groups convened to preview upcoming topics to be covered in the classroom, to discuss teacher experiences with implementing the units, to discuss successes, and to problem solving failures. The groups were led by a study facilitator with expertise in either content or the cognitive science principles (Massey, Cleland, & Mandel, 2013).

Outcome Measures

For the randomized control trial, we used state assessment scores and an end-of-unit test we developed and aligned to the content of the intervention PD for each unit. Previous research has shown that standardized assessments can be less sensitive to the results of an intervention (May, Perez-Johnson, Haimson, Sattar, & Gleason, 2009; Olsen, Unlu, Jaciw, & Price, 2011; Somers, Zhu, & Wong, 2011), so we wanted to also have a more proximal measure of student achievement. Each test comprised 18 items drawn from a pool of publicly released items from state tests (from nonstudy states), the National Assessment of Educational Progress, and the Trends in International Mathematics and Science Study. We used a validated metric to align questions to the content of the unmodified curriculum, so as not to bias the assessments in favor of the intervention arm teachers, who used the modified curriculum.

Findings from the Experimental Study

Findings from the larger study (see Scull, Porter, Massey, & Merlino, 2016; Yang, Porter, Massey, & Merlino, 2016), reported in (Yang, Porter, Massey, & Merlino, 2016) show that students of teachers in the cognitive science arm of the study showed more improvement in science knowledge, compared with students of teachers in the content or control arms, although usually the difference was not statistically significant. The most consistent significant result was when comparing the cognitive science arm with the content arm on a state standardized test. However, there were not significant differences when examining the specifically constructed test that was aligned to the PD content (Yang, Porter, Massey, & Merlino, 2016). These findings provide the foundation for exploring one set of relationships that may help explain the differential effects: the relationship between teachers' content knowledge and what they learn in PD.

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[1] Teachers who teach multiple units included in the intervention could have up to three sets of the 34-hour PD sessions.

Methods

Sample

Table 1
Characteristics of Interviewees

Name	Arm	Years of experience	Undergraduate major	Cognitive science principles implementation score for geology unit	Teacher content knowledge scores
Molly	Cognitive science	3	Geology	2.90	16
Emily	Cognitive science	8	Education	2.62	19
Monica	Cognitive science	28	Education	2.84	19
Jasmine	Cognitive science	2	Biology	3.21	20
Andrew	Cognitive science	3	Geology	3.13	22
Mike	Cognitive science	2	Social science	2.78[b]	22
Clare	Content	23	Education	2.29	21
Barry	Content	3	Science	—	21
Bob	Content	8	Business	—	22
Malik	Content	7	Social science	2.58	17
Angela	Control	10	Education	2.52	19
Lisa	Control	9	Design	2.81	19
Lloyd	Control	15	Education	2.42	11
Harry	Control	6	Education	2.67	14

Notes: Cognitive science principles implementation score for geology for full sample (Mean=2.69; *SD*=0.30; Range=2.13–3.56)[a] and teacher content knowledge scores for full sample (Mean=19.12; *SD*=3.08; Range=8–25); [a]The focus of this measure was how teachers in the cognitive science arm implement cognitive science principles; therefore we do not expect teachers in the content arm to have higher implementation scores than control teachers. [b]We do not have data from all of the teachers for their implementation scores from the second year of our study. For Mike, we include his first year implementation score.

The larger intervention study included teachers in two large cities in the southwestern United States and two large cities in the eastern United States. We selected one of the eastern cities (N=87) to conduct our in-depth interview study. We focused our investigation on a single unit in order to probe more deeply into content knowledge and implementation issues. We chose to focus on geology, which is an earth history unit, because it was taught in the winter, when it was less likely to be interrupted by standardized testing.

We selected 14 teachers from the three arms of the study to reflect on their PD experiences and resulting changes in their instruction. We chose six from the cognitive science arm (overrepresented because the focus of the larger study was on use of cognitive science principles),

four from the content arm, and four from the control group. Our goal in selecting teachers was to have teachers with the largest exposure to the intervention because these teachers would be more likely to show effects on knowledge and instruction (e.g., Yoon, Duncan, Wen-Yu Lee, Scarloss, & Shapley, 2007). We selected teachers who were in their second year of participating in the study, because research finds that one year of intervention use may not be enough to learn how to use the intervention materials (Borman et al., 2008; Fullan, 1991). Also, we selected cognitive science teachers with the highest number of PD hours for the unit and who taught multiple sections of science, because they had the largest dose of the cognitive science intervention and more opportunities for implementation. Finally, we included teachers from the control arm in order to compare varying levels of content and content-plus-pedagogy PD delivered by researchers within our study to PD delivered outside of the context of our study. The characteristics of the teachers who participated in our interviews are provided in Table 1. We recognize that teachers may also vary in ways not reflected in our measures. However, given that this is an exploratory study, we are seeking patterns of relationships that can be tested with future research.

Data

Several data sources informed this study. Quantitative data were collected from a detailed teacher implementation survey, as well as a researcher-created CK test given to teachers in the cognitive science, content, and control arms of the study. The implementation scores we use in this study are a measure of the frequency with which the teachers follow the cognitive science principles. A higher score indicates that the teacher has higher fidelity of implementation. While content and control teachers did not receive explicit instruction on the cognitive science principles, we measure their frequency of use of these principles as well. Qualitative data come from teacher interviews, which were recorded and transcribed. We conducted interviews in the winter of the 2011–2012 school year. We used the larger study's quantitative database to identify the teachers who fit our criteria. Sorting the teachers with the greatest number of PD hours, we contacted individual teachers to ask for their participation. For the control teachers, we selected teachers who would be teaching the unit for the second time to multiple classes. Each interview was conducted at the teachers' schools. The interviews were scheduled for 2 hours and in practice ranged from 45 minutes to 2 hours. For each interview, we used a detailed interview protocol that covered teachers' perceptions of the goals of the PD, a description of how the teacher taught a particular lesson, and facilitators of and barriers to science instruction. Since the control teachers did not receive PD as part of the study, we asked about any PD that they experienced. To maintain confidentiality, we used pseudonyms for the teachers.

In analyzing the interview data, we followed the procedures outlined by Miles and Huberman (1994), Huberman and Miles (1994), Patton (1990), and Coffey and Atkinson (1996). Our conceptual framework and research questions served as the basis for our initial coding framework for interview transcripts (Alexander, 2001). We then added more themes and subthemes as called for by our ongoing analysis of the transcript data. We used the constant comparative method to develop the codes (Glaser & Strauss, 1967; Strauss & Corbin, 1998) so that ideas from the transcripts were used to expand and refine the coding system. Through this iterative process, we changed, adapted, and integrated categories or themes (Goetz & LeCompte, 1984). In this way, we were able to interactively identify themes using both our conceptual framework as well as the transcript data. This method enabled us to use the data to inductively test our hypotheses, as well as to deductively allow other themes and explanations to emerge that we had not anticipated in our conceptual framework (Emerson, Fretz, & Shaw, 1995; Green, Dixon, & Zaharlock, 2002). The codes we used were derived from our framework and the literature and included, but were not

limited to, the following categories: perception of content knowledge in science; experience with science teaching; confidence in science; description of learning in the PD and changes in instruction; understanding of the PD goals; understanding of the cognitive science principles; self-assessment of student science learning, engagement, and motivation; relevant school or classroom context/conditions; interacting with other teachers; and teacher autonomy. We illustrate each key theme with key quotes as exemplars (see Atkinson, Coffey, & Delamont, 2003), a technique that, according to Ryan and Bernard (2003), is "a widely used method for describing themes . . . that lead the reader to understand quickly what it may have taken the researcher months or years to figure out" (p. 282). Given the modest size of our sample, we thought it prudent to try to reflect the continuum of teacher experiences rather than focus only on those issues that "most" teachers discussed. Overall, however, most key themes were reflected in the majority of teacher interviews.

Measuring Teacher Content Knowledge

In addition to influencing student learning, prior knowledge also plays a critical role in teacher learning. Understanding and assessing teacher CK has been the focus of considerable research (Ball, 1990, 1991; Ball & Rowan, 2004; Ball, Lubienski, & Mewborn, 2001). Teacher CK has been operationalized in multiple ways, including college major, course taking, years of experience, certification, and test scores (Sadler, Sonnert, Coyle, Cook-Smith, & Miller, 2013). While evidence is mixed in relating these variables to instructional quality and student learning (e.g., Wilson, Floden, & Ferrini-Mundy, 2002), college major has been shown to be related to student achievement (Goldhaber & Brewer, 1997, 2000; Rowan, Chiang, & Miller, 1997). Our choice to use college major as the measure of teachers' CK is guided by this general finding that using major as a proxy for teacher CK is consistently correlated with expected teacher and student outcomes. Perhaps more importantly, teachers in our study who had an undergraduate major in science *perceived* themselves as much stronger in CK than teachers without such a degree. We found this a compelling factor in our decision about how to classify teachers' CK, given that our investigation is primarily concerned with teachers' views of their own CK and how they believe their CK influenced what they learned from the PD.

This is not to discount the considerable CK growth that can occur through other mechanisms, such as years of teaching particular subject matter to students, participating in in-service learning opportunities, self-guided subject-matter reading, and many more. Investigating the relationship between multiple measures of teachers' CK is beyond the scope of this study. That being said, we do note that teacher scores on the CK test we created and administered as part of the study were generally, though very weakly, related to undergraduate major. For the teachers we studied, the average CK score was 18.7 (range 8-25) (see Table 1), with little difference between those with and without a science major—on average, those with a science major scored a 19.75 and those with a non-science major scored 18.30. While the CK test we created was reliable and valid (Porter, Polikoff, Barghaus, & Yang, 2013), it measures a very narrow domain of middle school science (as is the nature of most tests) and as such was unlikely to capture much of the differences in what teachers know about middle school science and how to teach it.

We recognize that teacher CK is complex, and is not fully represented by undergraduate major, a knowledge test, or any other single measure. We feel comfortable using undergraduate major as an indication of CK here given the exploratory nature of our study, and given the correlation between undergraduate major and teachers' description of their confidence and comfort level with teaching science.

Results

Our analysis uncovered several themes regarding teachers' learning in the content-only and cognitive science interventions. We describe these themes below as lessons, each contributing to a deeper understanding of the role of CK in the effects of PD on teachers.

Lesson 1: What Teachers Learn and Do as a Result of High-Quality Content PD Depends on Their Prior Knowledge

We find that when teachers participated in the high-quality content-focused PD offered in our study, what they perceived that they learned and did as a result depended on their prior CK. Through our analysis of the teachers in the content-only arm, we found that teachers with weak prior CK (i.e., a nonscience major) made gains on multiple dimensions: CK, PCK, and affective factors such as confidence. However, if teachers already had substantial CK in the content area covered, they tended to focus on increasing only their PCK.

Clare, who was in the content-only arm and did not have a science background, found that the content PD helped her broaden and deepen her CK. Clare was a 23-year teaching veteran who, by her own admission, struggled with advanced science concepts:

> [Before the PLCs] I basically taught sticking to the facts that come from the book, but after the PLCs and after the professional development they pointed out how the book has some misconceptions, so that was an eye-opener for me because … there was some other things that I learned that I had been teaching and it was wrong because of the information that I was getting from the text.

Clare felt that the content intervention PD helped her build her knowledge of science, and she indicated that as a result of her increased CK, her confidence significantly increased and empowered her to deviate from the curriculum. She described how her limited knowledge of science content made it difficult to answer questions from more advanced students and stifled classroom conversations. However, the additional CK learned in the PD helped her to answer those questions, and participation in the PLCs gave her "a little bit more heart" to venture away from the district pacing guide. Since the PD, Clare applied her content PD experiences to her classroom in such a way that empowered her to take instructional risks. She stated that her increased confidence in teaching made her more comfortable when engaging with her more advanced students. She was better able to support risk-taking in her class, which significantly increased student curiosity.

Like Clare, Lisa, a control teacher, also experienced high-quality content PD through taking a physics course at a local university. While the PD of the course was not specific to geology (our discipline of interest), her response as a control teacher, who did not receive any specific PD from us, illustrates that high-quality content PD can help improve understanding and confidence. When probed to describe the ways the PD broadened her understanding, Lisa stated that the physics course changed her instruction and her confidence in teaching. She said,

> The physics course made me understand…chemistry in a whole new way and that happened at the very beginning when …we talked about energy and the energy of elements and the energy of everything, of matter period. And so when I went to go teach my kids about what's the difference between a gas, a liquid and a solid, I taught

> it to them in terms of, who's got the most energy? Like who's moving the fastest
> and, and what are they doing with that? And so it, it broadened my horizons you
> know in … my understanding and the way that I approach teaching it to the kids
> changed.

When asked to describe how the PD changed her knowledge of science, Lisa went on to say that she felt more comfortable having classroom discussions with her students because she had more confidence in her knowledge and an increased willingness to admit that she did not know the answer to every question.

Clare's and Lisa's learning trajectories resemble the solid arrow lines in Figure 1. Both came to high-quality content-focused PD experiences with weak prior CK, and through their experiences they believe that they increased their CK as well as their confidence in their teaching abilities. The experiences of Clare and Lisa are precisely what previous research would predict, in that building teachers' CK enables them to probe more deeply and to feel more comfortable with material, which in turn leads teachers to engage in more exploratory discussions with students, to experiment more with ideas, and to rely less heavily on the text (e.g., Cohen et al., 1993). The PD provided them with the opportunity to fill in gaps in their CK and build their confidence.

Filling gaps in CK was not the only response for teachers participating in high-quality content-focused PD. Although the content-only arm did not explicitly provide lessons or strategies, some teachers still indicated that the main takeaways were related to new instructional activities rather than building their CK. For example, Malik, a teacher with a social science background and weak science CK, when asked to what extent the PD changed his pedagogy, indicated that the PD gave him new ideas and expanded his knowledge base, which gave him more confidence. Although he told us that his knowledge base increased, he talked more about how the PD helped increase his knowledge of how to do activities in his classroom. He said,

> I mean there was a lot of things obviously I didn't know because … it was like my
> second… certification and … it helped me to … understand things better and …
> you know thinking about … how I'm gonna do different activities and gave me like
> more of a strong knowledge of, of the subject area…. I use like a lot of the, like the
> activities that, that we learned the material from and you know even like ways I look
> at rocks, look at you know the different specimens and how to like describe all those
> things, like what we had to do in, in the class. Then … I would turn around and I
> would use like a lot of that stuff, you know a lot of that knowledge in the classroom.

Despite claims of increased content knowledge, Malik primarily talked about ideas for activities rather than the CK that he gained. Based on Malik's description of his learning, it does not appear that he increased his CK despite his claims that he did. Instead, descriptions of his activity usage indicate that he increased his PCK as well as his confidence and comfort with teaching science.

The cases of Clare, Lisa, and Malik show that teachers with weak CK can have a variety of learning outcomes from high-quality PD even if it is focused specifically on CK. But when teachers already have strong prior CK, we found that what they said they learned from PD differed substantially from their colleagues with weak CK.

Unlike other content-arm teachers Malik and Clare, Barry had mastered middle school science content. He had a master's degree in geological science and had worked as a geologist. Despite the content PD being devoid of explicit attention to pedagogy, during the PD sessions Barry focused on *how* the facilitators were presenting the material to the teachers. He said,

> I spent my time because I felt comfortable in the content, I knew I wasn't
> gonna get, oh this website has this, this website is, you can get this handout
> or this flyer from this location or that location, I spent my time taking notes
> in the margin trying to say, oh this was really good, find out how or where
> this came from [in terms of delivery of the content]…so in that aspect it
> helped me significantly.

In this case, since Barry already had mastered the CK that was the focus of the PD, he found a way to make the PD useful—he focused on aspects related to *how* the presenters conveyed information.

These cases highlight a continuing challenge for those who design and study PD: the relative emphasis that should be placed on pure CK, on one hand, and instructional or pedagogical strategies, on the other. One hypothesis is that building teachers' CK is enough and it will translate into better instruction through multiple mechanisms, such as asking deeper questions and understanding student mistakes (Hill et al., 2008). Another hypothesis is that while certain high-performing teachers may be able to take increased CK and translate it into better instruction, more consistent and stronger effects are found if the PD includes explicit links to lessons, activities, and strategies that the teachers can readily translate and integrate into their classroom instruction (Penuel et al., 2007). Turning now to the arm of the study that targeted the application of cognitive science principles as a way to provide teachers with both new knowledge and new pedagogical strategies provides insights into the apparent tension between content-only PD and content-plus-pedagogy PD.

Lesson 2: What Teachers Learn and Do as a Result of High-Quality Content-Plus-Pedagogy PD Depends on Their Prior Knowledge

Our cognitive science arm teachers were split evenly between strong and weak prior CK, as indicated by their undergraduate major (as shown in Table 1). As we analyzed the data, we found that these two groupings aligned with (a) the extent to which the teachers understood the underlying cognitive science theory and (b) based on our assessment of their reflections on teaching and a measure of implementation from teacher surveys, the fidelity with which they implemented the cognitive science intervention. Teachers who already had the CK were able to describe a deeper understanding and higher level of implementation than other teachers. Based on quantitative measures of implementation of the cognitive science principles from teacher surveys (see Table 1) and qualitative evaluations of implementation from teacher interviews, the three teachers with the highest level of implementation were Jasmine, Andrew, and Molly, all three of whom have undergraduate degrees in science. The teachers who did not describe a deep understanding of the cognitive science principles and had lower levels of implementation—Monica, Mike, and Emily— had an elementary education or social science background.

Jasmine's, Andrew's, and Molly's self-reported learning and change as a result of the cognitive science PD resemble the dashed arrow line in Figure 1. All three had strong science backgrounds. They saw little gain in CK, but they did find that they gained in their PCK; these gains were in the ways that the PD designers had intended. In contrast, the teachers with lower levels of prior CK tended not to describe increases in their PCK, but instead reported making gains in CK and/or affective outcomes such as confidence and risk taking. We found evidence of the association between teacher CK and understanding or implementation in three areas: the level of understanding of the cognitive science principles, the extent to which teachers viewed the intervention as a script, and the extent to which they transferred ideas from the target unit to other subjects and classes.

Understanding the cognitive science principles. Cohen (1990) painted a powerful picture of a teacher making an effort to implement a new teaching strategy without mastery of the underlying principles. He described how "Mrs. Oublier" introduced mathematical manipulatives to her students; she did not seem to know their purpose or how to use them. She asked the children to touch them as if they had "magical instructional powers" (Cohen, 1990, p. 318). This demonstrated that Mrs. Oublier was following the intervention's procedures to have the children use the manipulatives but did not understand *how* the manipulatives aided student learning.

Our findings are analogous to Cohen's, in that there was variation in the extent to which teachers viewed our intervention as a set of strategies to implement in the classroom without demonstrating understanding of the underlying principles behind the strategies; and we found a positive relationship between teachers' depth of understanding of the principles and those teachers' CK.

Andrew, a third-year science teacher with an undergraduate major in geology, described the PD as providing theory and research on the principles underlying the use of the cognitive science principles. Andrew recognized that the PD provided the teachers with more than a binder of lesson plans for the geology unit; however, he also recognized that teachers need to implement the activities correctly. He described the goals of the PD as follows:

> [The l]arger scale [goals] I guess [were about] helping us as the teachers use the materials to the best of our abilities. I mean the work of getting the materials created and understanding the principles and the study involved of whether or not are these gonna work the best? Is this a different way of teaching that will allow the students to understand the concepts better, but the goal, you know these are worthless unless the teacher can actually use them effectively.

Molly, who like Andrew was a third-year science teacher with a geology undergraduate major, also saw the PD as a source of information about the underlying theory of cognitive science. When asked about the goals of the PD sessions, she said, "I think the goals were just to get us to understand why we were doing it in terms of how students learn and the cognitive development that they have." Both Andrew and Molly articulated the underlying theory throughout their interviews. For instance, in Molly's interview she focused on how the PD helped her see how students understand relationships among scientific concepts. As a result, she said that her instruction changed to focus on the *big ideas* within a unit rather than on the individual facts, which was a goal of the intervention designers. This change in instruction indicates that she internalized the underlying cognitive science theory behind the intervention.

In contrast, the other teachers whom we interviewed in the cognitive science arm of the study viewed the PD primarily as a source of materials for their classroom. For example, Emily, an eighth-year science teacher with an undergraduate major in elementary education, told us that the PD provided her with the chance to learn how to conduct activities with her students. She went on to say,

> The one thing that we did that was really helpful because it was kind of a confusing activity was the Contrasting Case with the time lines…. And that was helpful, very helpful because when you first look at those, you're like, oh are our kids really gonna understand that, but then they … by doing it with us they were able to say … you know this is what they're gonna see and this is what they're supposed to get out of it.

In contrast to Andrew and Molly, Emily did not talk about gaining knowledge about the underlying principles of the cognitive science intervention. Instead, her concern and focus were on being able to repeat the activities on her own.

Another clear contrast between the teachers who understood the underlying concepts of the intervention and those teachers who did not emerged from teachers' responses when asked *why* they used warm-ups, a component of the CSM, in their classrooms. Once again, there emerged a group that understood the underlying concepts and those that did not, which aligned with whether or not the teacher had strong prior CK.

Andrew viewed warm-ups as a method for assessing student understanding, which is the purpose intended by the intervention. In contrast, Monica used warm-ups as a behavioral tool rather than an assessment tool, saying,

> I just think it's a good way of just setting the tone, bringing them in, you
> know they're, they're coming from upstairs on the third floor, they've had 3
> floors, 66 steps to chittychat and when you just go, okay let's get right into it,
> okay yesterday and they hear that word yesterday they get quiet and boom
> we're right into it.

These examples of how teachers described their understanding and used the cognitive science principles suggest that the teachers with strong prior CK were able to increase their PCK. They tended to understand the main goals of the intervention and the modifications.

Is it a script or a set of principles? We found that teachers with stronger CK tended to describe their use of the CSM as a resource, while teachers with weaker CK were more likely to describe their use of the CSM as a scripted lesson plan. Although the CSM is not explicitly scripted, some teachers viewed it as a script, due in part to the fact that it provided day-by-day lessons.

Most of the teachers in the cognitive science arm of the study described the CSM modifications as a set of lessons and activities that saved them valuable planning time, and they embraced the CSM. However, the level of adherence to the CSM varied based on teacher comfort with its content. Emily, who had little science background, strictly followed the CSM. Prior to participation in the study, Emily strictly followed the district's curriculum plan. She indicated that the CSM replaced the district curriculum as her instructional script, saying, "[Using the CSM] changed [determining what is important from a lesson] simply because I follow what they do instead of following what the school district wants me to do." Emily relied on the material that she was given, either by the intervention or the district, to guide her instruction. Given that Emily tends to simply follow the materials that she is given rather than engaging with the material, we argue that she did not implement the intervention in a deep and meaningful way.

Similarly, Monica, who has a degree in elementary education, viewed the CSM as a step-by-step guide to instruction. She said,

> That is in … the notebook, so therefore that works really well that if it says, at this
> point you need to remind students about, or at this point you need to clarify a
> misconception that students might have about. So … it's bringing you back, it's
> grounding you, it's going, oh yeah, that's right, I need to do that.

Rather than internalizing the cognitive science principles, such as being able to anticipate when students will have misconceptions, Monica describes the intervention as providing her with materials

that explicitly told her the steps that she needed to take. Monica's responses indicated that she went through the motions of the intervention without fully understanding why she did each step.

Unlike Emily and Monica, Molly and Andrew used the intervention materials as guides to lessons rather than as scripts. Molly supplemented the CSM when she felt it was appropriate by adding labs and other activities to increase student engagement. And although Andrew did not think of the intervention materials as a script to be strictly followed, he did rely on the CSM as a time-saving source of lesson planning. He said,

> I mean I would, would've had to like make up my own ways of which to teach things and my own ideas about how to incorporate those things on the sidebar into the lessons, the actual day to day lessons of what, how that material's gonna be taught…I mean this, this is like you know thousands and thousands of hours of, of highly educated people coming up with these, these modifications, so I'd rather stick to the script, not that this is scripted, but stick to the ideas and principles behind teaching that are developed through this program.

Andrew recognized that the intervention focused on the cognitive science ideas and principles behind the activities; however, he also took advantage of the lesson plans and structure provided by the CSM and focused his energy on the additions that he could make to the geology unit.

When we examined whether or not teachers viewed the materials as a script, we found that the teachers with weak prior CK tend to focus on the activities and the CSM as a script. These teachers described going through the motions of the activities, but we have little evidence that they truly implemented the principles behind the activities. On the other hand, the teachers with strong prior CK used the materials as a starting point, supplementing the material with other activities, rather than viewing them as scripts to which they must adhere.

From principles to practice. One goal of the cognitive science intervention was for students to transfer the underlying cognitive science principles they learned to other topics and content areas. Although this particular intervention was geared toward middle school science, the underlying principles are not content specific. The same goal of transfer can be applied to teachers. If teachers truly understood and implemented the cognitive science principles, they should have been able to engage in pedagogical practices that reflect these principles with other instructional content outside of the focal geology unit. Once again, we saw differences in transfer based on teacher CK.

Monica, one of the teachers with low prior CK, highly praised the cognitive science intervention. However, she did not believe that she could create similar lessons for units other than those in the intervention, suggesting a lack of understanding of the cognitive science principles. When asked if she tried to use the cognitive science materials in other courses, she responded, "Well it's hard because you wouldn't have your day 1, day 2, you don't have a CD to go with it, that's where your movies come in you know?" This statement suggests that Monica did not view the intervention as an underlying theory for *how* to instruct students but instead saw it as a source of pre-made lesson plans.

In contrast to Monica, Jasmine, a second-year science teacher with an undergraduate biology major, tried to use cognitive science principles for units for which she did not have the CSM. She said, "You know in the other units that I don't have the [CSM], I've tried, I mean I don't make up Contrasting Cases, but I do have, do a lot of comparing and contrasting. So I try to incorporate some of the things that are in the [CSM] into my other, other units." Using the cognitive science principles in other units suggests that the teacher regards the intervention as more than a source of

lesson plans or a series of activities to cover with students. By attempting to use the cognitive science approach in nonintervention units, teachers demonstrated that they recognized that the principles can be applied to any material.

We saw clear patterns of teachers with strong prior CK increasing their level of PCK. At the same time, we saw teachers with weak CK making superficial changes in their pedagogical practices. However, this does not mean that the cognitive science PD was not successful in providing teachers with new knowledge. Because the teachers with strong prior CK did not necessarily need to focus their attention on the content that was being presented, they were able to make gains in pedagogical skills. The teachers with weak prior CK, on the other hand, tended to focus their attention on the actual content being presented through the activities and modifications.

Lesson 3: Teacher Emphasis on Gaining CK versus PCK Depends on Prior Knowledge

As we have indicated, the cognitive science PD was designed to provide teachers with an opportunity to learn how to use cognitive science principles in their teaching, and the PD provided them with detailed lessons and activities for how to do that for a particular science unit. The PD was not designed to increase teachers' CK in middle school science—it presented no new content other than what was covered in the district's pacing guide. Although we certainly found that some teachers in the cognitive science arm did understand and use the pedagogical strategies in their classrooms, we also found that other teachers in the cognitive science arm reported gaining more in *content* knowledge than in pedagogical strategies.

Teachers with science degrees in our cognitive science arm indicated that the PD did not substantially increase their CK, with the exception of a very few specific information points. In contrast, teachers without a science background who participated in the cognitive science PD reported building their CK. We found that teachers focused their own learning to be consistent with their level of science content mastery; those with weak CK focused on the content, while those with science backgrounds moved beyond the content to learn the principles and applications.

Emily, a teacher without a science background, is a good example of this phenomenon. Prior to participating in the intervention PD, Emily reported using the textbook as her source of information about science; she said that she learned the content along with her students. She was unfamiliar with much of the geology unit material, and she admitted to having misconceptions about the content. She often did not know the answers to student questions and had to look up the answers. In discussing her experiences in the cognitive science PD, she said that the intervention helped her gain a better understanding of the geology unit content. She went on to say, "Like I feel like I can stand in front of the class and not have to look at my book to say, you know this is this, this is this, I can just say to them, like I'm teaching them instead of reading it."

As we discussed above, Emily implemented the modifications by following the CSM as a script, and she did not demonstrate a deep understanding of the intervention itself beyond its use as a pacing guide. We hypothesized that this was because her CK was so weak that her main focus during the PD was on gathering the CK that she lacked rather than internalizing the pedagogical concepts that were presented in the cognitive science PD.

Discussion

Providing effective PD is central to the success of many school improvement policies. In this study we explored how teacher CK may explain variation in what teachers learn and do as a result of PD, and how teacher knowledge and features of the PD may interact to explain differential

effects of PD on teachers. Results should be interpreted in light of the several limitations. Our study is exploratory, and thus patterns we see need to be examined on a larger scale. Further, our interview and survey data are self-reported, which has both strengths and weaknesses (Mayer, 1999).

Despite these limitations, we believe our results provide important insights for developing PD policy. We found that, with both the content-only and the content-plus-pedagogy interventions, teachers used PD to fit their needs, depending on their previous CK in the subject (which in this case is science). Even though not all teachers learned what the PD designers intended for them to learn, they did report learning something that could help them improve as teachers.

Teachers in the cognitive science arm who came to their PD with strong CK were much more likely to describe a deep and meaningful understanding of the cognitive science principles, and to describe how they integrated these principles into their teaching in meaningful ways. In contrast, teachers with weak science CK used the PD as a way to bolster their CK, and used the cognitive science intervention as more of a script to follow. Returning to Figure 1, the teachers in the cognitive science arm with the strong CK background generally followed the dashed line arrow, noting gains in their PCK. On the other hand, teachers in the cognitive science arm with weak CK generally followed the solid path, describing more of an increase in CK than in PCK when reflecting on their growth.

We found a similar pattern of differentiation in the content-only PD. There, teachers with strong CK focused on learning from the PD delivery activities as new ways to present material. Across both the content-only and cognitive science arms, we also found examples of teachers with weak prior CK gaining knowledge from the PD in ways that seemed to translate to better instruction, as previous research would suggest. These teachers felt that their confidence had increased and that they were better able to answer their students' questions, making them better science teachers.

Policy Implications: Differentiating PD

In the context of the broader literature that emphasizes the importance of teacher quality, and the critical role that PD plays in supporting teachers in effectively implementing instruction aligned to new math, English language arts, and science standards (e.g., Marrongelle, Sztajn, & Smith, 2013), our work has direct implications for how districts and schools might structure PD better to improve its effectiveness.

Specifically, our findings suggest implications for how PD is designed and provided as well as how its effectiveness is determined. Despite substantial progress in developing a consensus around core features of high-quality PD, there has been little call for differentiated PD, or activities calibrated to the needs and learning levels of particular teachers. These ideas are not completely new, however. Santagata et al. (2012), in discussing variation in teacher response to a PD intervention, suggest gauging PD to teachers' knowledge and needs. In asking what types of content knowledge are necessary for effective teaching, Diamond et al. (2014) leave open the idea that such knowledge may differ across teachers. Other researchers recommend considering knowledge and experience differences among teachers in designing PD (Loucks-Horsley Stiles, Mundry, Love, & Hewson, 2010) and personalizing PD to address teachers' particular circumstances and challenges with instructional practices (Bitan-Friedlander et al., 2004; Starkey et al., 2009).

Our findings lend support to the idea of differentiating PD. They show that what teachers learn in PD depends on what they already know. This may seem obvious, but current models of "one size fits all" PD do not reflect this reality. Our data suggest that teachers can take away very different information and strategies from a learning experience, depending on the knowledge they

bring to the activity, as well as their own proclivity and assessment of where they would like to improve. The PD may not have the intended outcome if teachers have varying responses and learning from the PD. Focusing on high-quality PD is not enough; we need to think more about how the PD interacts with teachers' previous knowledge and experiences.

Our findings suggest how important CK may be for developing deep understanding, echoing other research prioritizing the role of CK in teachers' instructional development (e.g., Cohen & Hill, 2001; Lee & Luft, 2008; Ma, 1999). But our findings go beyond that to suggest different ways that teachers can benefit from high-quality PD and how this may be systematically related to their CK. Further, we provide insights into how a PD consisting of a set of principles, activities, and lessons can provide some teachers with an opportunity to gain deeper ideas about instruction and ways of presenting material while simply providing other teachers with a lesson plan to follow, perhaps with "magical instructional powers" (Cohen, 1990, p. 318) of its own.

How a teacher reacts plays a large part in determining the extent to which an intervention changes what teachers know and how they think. It is not just the intervention itself that matters, but the interaction between teachers' knowledge and their PD experience. While some PD interventions have shown reasonable average effects, many more vary in their effects by measurable characteristics such as teacher experience (e.g., Borman et al., 2008), and some very intensive PDs have had little effect on instructional practice and student achievement (e.g., Garet et al., 2010). We hope that the ideas presented here will play a role in interpreting these studies.

Designing PD that is calibrated to teachers' needs and prior knowledge holds great promise for increasing the payoff for PD. This could be especially important in light of millions of dollars currently going to developing PD to support Common Core State Standards implementation in the United States. Further, knowledge of the variation in what teachers learn and do as a result of the same PD experiences contributes to our understanding of when and how PD affects teacher learning, and could help us become more sophisticated in how we measure and interpret findings of PD effectiveness studies.

References

Alexander, R. (2001). *Culture and pedagogy: International comparisons in primary education*. Malden, MA: Blackwell.

Atkinson, P., Coffey, A., & Delamont, S. (2003). *Key themes in qualitative research: Continuities and change*. Walnut Creek, CA: AltaMira Press.

Ball, D. L. (1990). The mathematical understandings that prospective teachers bring to teacher education. *Elementary School Journal, 90*(4), 449–466. http://dx.doi.org/10.1086/461626

Ball, D. L. (1991). Research on teaching mathematics: Making subject matter part of the equation. In J. Brophy (Ed.), *Advances in research on teaching* (Vol. 2; pp. 1–48). Greenwich, CT: JAI Press.

Ball, D. L. (2000). Bridging practices: Intertwining content and pedagogy in teaching and learning to teach. *Journal of Teacher Education, 51*(3), 241–247. doi:10.1177/0022487100051003013

Ball, C., & Cohen, D. (1999). Developing practice, developing practitioners: Toward a practice-based theory of professional education. In L. Darling-Hammond & G. Sykes (Eds.), *Teaching as the learning profession: Handbook of policy and practice* (pp. 3–32). San Francisco, CA: Jossey-Bass.

Ball, D. L., Lubienski, S. T., & Mewborn, D. S. (2001). Research on teaching mathematics: The unsolved problem of teachers' mathematical knowledge. In V. Richardson (Ed.), *Handbook of research on teaching* (4th ed.; pp. 433–456). Washington, DC: American Educational Research Association.

Ball, D. L., & Rowan, B. (2004). Introduction: Measuring instruction. *Elementary School Journal, 105*(1), 3–10. Retrieved from http://www-personal.umich.edu/~dball/articles/Ball_Rowan_ESJsept04_SIIissue.pdf http://dx.doi.org/10.1086/428762

Ball, D. L., Thames, M. H., & Phelps, G. (2008). Content knowledge for teaching: What makes it special? *Journal of Teacher Education, 59*(5), 389–407. doi:10.1177/0022487108324554

Bitan-Friedlander, N., Dreyfus, A., & Milgrom, Z. (2004). Types of "teachers in training": The reactions of primary school science teachers when confronted with the task of implementing an innovation. *Teaching and Teacher Education, 20*, 607–619. doi:10.1016/j.tate.2004.06.007

Borko, H. (2004). Professional development and teacher learning: Mapping the terrain. *Educational Researcher, 33*(8), 3–15. doi:10.3102/0013189X033008003

Borko, H., Eisenhart, M., Brown, C. A., Underhill, R. G., Jones, D., & Agard, P. C. (1992). Learning to teach hard mathematics: Do novice teachers and their instructors give up too easily? *Journal for Research in Mathematics Education, 23*(3), 194–222. doi:10.2307/749118

Borko, H., & Putnam, R. (1996). Learning to teach. In D. Berliner & R. Calfee (Eds.), *Handbook of educational psychology* (pp. 673–708). New York, NY: Macmillan.

Borman, G. D., Gamoran, A., & Bowdon, J. (2008). A randomized trial of teacher development in elementary science: First-year achievement effects. *Journal of Research on Educational Effectiveness*, *1*(4), 237–264. doi:10.1080/19345740802328273

Boyd, D., Grossman, P. L., Lankford, H., Loeb, S., & Wyckoff, J. (2009). Teacher preparation and student achievement. *Educational Evaluation and Policy Analysis*, *31*(4), 416–440. doi:10.3102/0162373709353129

Bransford, J. D., & Schwartz, D. L. (1999). Rethinking transfer: A simple proposal with multiple implications. *Review of Research in Education, 24*, 61–100. http://www.jstor.org/stable/1167267

Buczynski, S., & Hansen, C. B. (2010). Impact of professional development on teacher practice: Uncovering connections. *Teaching and Teacher Education, 26*, 599–607. doi:10.1016/j.tate.2009.09.006

Chi, M. T. H. (2000). Self-explaining expository texts: The dual processes of generating inferences and repairing mental models. In R. Glaser (Ed.), *Advances in instructional psychology* (pp. 161–238). Mahwah, NJ: Erlbaum.

Chi, M. T. H. (2005). Common sense conceptions of emergent processes: Why some misconceptions are robust. *Journal of the Learning Sciences, 14,* 161–199. doi:10.1207/s15327809jls1402_1

Chi, M. T. H., Bassok, M., Lewis, M. W., Reimann, P., & Glaser, R. (1989). Self-explanations: How students study and use examples in learning to solve problems. *Cognitive Science, 13*, 145–182. http://dx.doi.org/10.1207/s15516709cog1302_1

Chi, M. T. H., De Leeuw, N., Chiu, M. H., & LaVancher, C. (1994). Eliciting self-explanations improves understanding. *Cognitive Science, 18*, 439–477.

Coffey, A., & Atkinson, P. (1996). *Making sense of qualitative data analysis: Complementary strategies*. Thousand Oaks, CA: Sage.

Cohen, D. K. (1990). A revolution in one classroom: The case of Mrs. Oublier. *Educational Evaluation and Policy Analysis, 12*(3), 311–329. doi:10.3102/01623737012003311

Cohen, D. K., & Hill, H. C. (2001). *Learning policy: When state education reform works*. New Haven, CT: Yale University Press. http://dx.doi.org/10.12987/yale/9780300089479.001.0001

Cohen, D. K., McLaughlin, M. W., & Talbert, J. E. (Eds.). (1993). *Teaching for understanding: Challenges for policy and practice*. San Francisco, CA: Jossey-Bass.

Darling-Hammond, L. (1997). *Doing what matters most: Investing in quality teaching*. New York: National Commission on Teaching & America's Future.

Davidson, M. R., Fields, M. K., & Yang, J. (2009). A randomized trial study of a preschool literacy curriculum: The importance of implementation. *Journal of Research on Educational Effectiveness*, *18*(42), 177–208. doi:10.1080/19345740902770028

Desimone, L. M. (2009). Improving impact studies of teachers' professional development: Toward better conceptualizations and measures. *Educational researcher*, *38*(3), 181-199. http://dx.doi.org/10.3102/0013189X08331140

Diamond, B. S., Maerten-Rivera, J., Rohrer, R., & Lee, O. (2014). Effectiveness of a curricular and professional development intervention at improving elementary teachers' science content knowledge and student achievement: Year 1 results. *Journal of Research in Science Teaching, 51*(5), 635–658. doi:10.1002/tea.21148

Domitrovich, C. E., Gest, S. D., Gill, S., Bierman, K. L., Welsh, J. A., & Jones, D. (2009). Fostering high-quality teaching with an enriched curriculum and professional development support: The Head Start REDI program. *American Educational Research Journal*, *46*(2), 567–597. doi:10.3102/0002831208328089

Emerson, R., Fretz, R., & Shaw, L. (1995). *Writing ethnographic fieldnotes*. Chicago, IL: University of Chicago Press. http://dx.doi.org/10.7208/chicago/9780226206851.001.0001

Fleer, M. (2009). Supporting scientific conceptual consciousness or learning in 'a roundabout way' in play-based contexts. *International Journal of Science Education, 31*(8), 1069–1089. doi:10.1080/09500690801953161

Fullan, M. (with Stiegelbauer, S.). (1991). *The new meaning of educational change*. New York, NY: Teachers College Press.

Garet, M., Birman, B., Porter, A., Yoon, K., & Desimone, L. (2001). What makes professional development effective? Analysis of a national sample of teachers. *American Education Research Journal, 38*(3), 915–945. doi:10.3102/00028312038004915

Garet, M. S., Cronen, S., Eaton, M., Kurki, A., Ludwig, M., Jones, W., Uekawa, K., … Silverberg, M. (2008). *The impact of two professional development interventions on early reading instruction and achievement*. Washington, DC: National Center for Education Evaluation and Regional Assistance, Institute of Education Sciences, U.S. Department of Education. Retrieved from http://ies.ed.gov/ncee/pdf/20084030.pdf

Garet, M., Wayne, A., Stancavage, F., Taylor, J., Walters, K., Song, M., Brown, S., … Doolittle, F. (2010). *Middle school mathematics professional development impact study: Findings after the first year of implementation* (NCEE 2010-4009). Washington, DC: National Center for Education Evaluation and Regional Assistance, Institute of Education Sciences, U.S. Department of Education. Retrieved from http://ies.ed.gov/ncee/pubs/20104009/pdf/20104010.pdf

Gentner, D., Loewenstein, J., & Thompson, L. (2003). Learning and transfer: A general role for analogical encoding. *Journal of Educational Psychology, 95*, 393–408. doi:10.1037/0022-0663.95.2.393

Glaser, B. G., & Strauss, A. L. (1967). *The discovery of grounded theory: Strategies for qualitative research*. Chicago, IL: Aldine.

Goetz, J., & LeCompte, M. (1984). *Ethnography and qualitative design in educational research*. Orlando, FL: Academic Press.

Goldhaber, D. D., & Brewer, D. J. (1997). Why don't schools and teachers seem to matter? Assessing the impact of unobservables on education productivity. *Journal of Human Resources, 32*(3), 505–523. doi:10.2307/146181

Goldhaber, D. D., & Brewer, D. J. (2000). Does teacher certification matter? High school teacher certification status and student achievement. *Educational Evaluation and Policy Analysis, 22*(2), 129–145. doi:10.3102/01623737022002129

Gowlett, C., Keddie, A., Mills, M., Renshaw, P., Christie, P., Geelan, D., & Monk, S. (2015). Using Butler to understand multiplicity and variability of policy reception. *Journal of Education Policy, 30*(2), 149–164. doi:0.1080/02680939.2014.920924

Green, J., Dixon, C., & Zaharlock, A. (2002). Ethnography as a logic of inquiry. In J. Flood, J. Jensen, D. Lapp, & J. Squire (Eds.), *Handbook for methods of research on English language arts teaching* (pp. 201–224). Mahwah, NJ: Lawrence Erlbaum.

Grossman, P. (1989). A study in contrast: Sources of pedagogical content knowledge for secondary English. *Journal of Teacher Education, 40*(5), 24–32. doi:10.1177/002248718904000504

Grossman, P. L. (1990). *The making of a teacher: Teacher knowledge and teacher education*. New York, NY: Teachers College Press.

Hegarty, M., Kriz, S., & Cate, C. (2003). The roles of mental animations and external animations in understanding mechanical systems. *Cognition & Instruction, 21*, 325–360. doi:10.1207/s1532690xci2104_1

Heller, J. I., Daeler, K. R., Wong, N., Shinohara, M., & Miratrix, L. W. (2012). Differential effects of three professional development models on teacher knowledge and student achievement in elementary science. *Journal of Research in Science Teaching, 49*(3), 333–362. doi:10.1002/tea.21004

Hill, H. C., Ball, D. L., & Schilling, S. G. (2008). Unpacking pedagogical content knowledge: Conceptualizing and measuring teachers' topic-specific knowledge of students. *Journal for Research in Mathematics Education*, *39*(4), 372–400. Retrieved from http://www.jstor.org/stable/40539304

Hill, H. C., Rowan, B., & Ball, D. L. (2005). Effects of teachers' mathematical knowledge for teaching on student achievement. *American Educational Research Journal, 42*(2), 371–406. doi:10.3102/00028312042002371

Huberman, A. M., & Miles, M. B. (1994). Data management and analysis methods. In N. K. Denzin & Y. S. Lincoln (Eds.), *Handbook of qualitative research* (pp. 428–444). Thousand Oaks, CA.: Sage.

Ingvarson, L., Meiers, M., & Beavis, A. (2005). Factors affecting the impact of professional development programs on teachers' knowledge, practice, student outcomes & efficacy. *Education Policy Analysis Archives, 13*(10). Retrieved from http://dx.doi.org/10.14507/epaa.v13n10.2005

Jüttner, M., Boone, W., Park, S., & Neuhaus, B. J. (2013). Development and use of a test instrument to measure biology teachers' content knowledge (CK) and pedagogical content knowledge (PCK). *Educational Assessment, Evaluation and Accountability, 25*(1), 45–67. doi:10.1007/s10763-012-9384-6

Kurtz, K. J., Miao, C. H., & Gentner, D. (2001). Learning by analogical bootstrapping. *Journal of the Learning Sciences, 10*, 417–446. doi:10.1207/S15327809JLS1004new_2

Lee, E., & Luft, J. (2008). Experienced secondary science teachers' representation of pedagogical content knowledge. *International Journal of Science Education, 30*(10), 1343-1363.http://dx.doi.org/10.1080/09500690802187058

Little, J. W. (1982). Norms of collegiality and experimentation: Workplace conditions of school success. *American Educational Research Journal*, *19*(3), 325-340. http://dx.doi.org/10.3102/00028312019003325

Loucks-Horsley, S., Hewson, P.W., Love, N., & Stiles, K. (1998). *Designing professional development for teachers of science and mathematics.* Thousand Oaks, CA: Corwin Press.

Loucks-Horsley, S., Stiles, K.E., Mundry, S., Love, N., & Hewson, P.W. (2010). *Designing professional development for teachers of science and mathematics.* Thousand Oaks, CA: Corwin Press.

Ma, L. (1999). *Knowing and teaching elementary mathematics: Teachers' understanding of fundamental mathematics in China and the United States.* Mahwah, NJ: Lawrence Erlbaum.

Maerten-Rivera, J., Ahn, A., Lanier, K., Diaz, J., & Lee, O. (in press). Effect of a multi-year intervention on science achievement of all students including English language learners. *The Elementary School Journal.*

Maerten-Rivera, J., Huggins, C., & Adamson, K. (2013 November). *The development and validation of measures of teachers' science knowledge and teaching practices collected through surveys and classroom observations.* Paper presented at the annual meeting of the Florida Educational Research Association, Gainesville, FL.

Marrongelle, K., Sztajn, P., & Smith, M. (2013). Scaling up professional development in an era of Common State Standards. *Journal of Teacher Education*, *64*(3), 202–211. doi:10.1177/0022487112473838

Maskit, D. (2011). Teachers' attitudes toward pedagogical changes during various stages of professional development. *Teaching and Teacher Education, 27*, 851–860. doi:10.1016/j.tate.2011.01.009

Massey, C., Cleland, D. & Mandel, B. (2013). *Professional development interventions in a large-scale randomized controlled study of middle school science learning.* Invited symposium presented at

the Fall 2013 Conference of the Society for Research on Educational Effectiveness. Washington, DC.

May, H., Perez-Johnson, I., Haimson, J., Sattar, S., & Gleason, P. (2009). *Using state tests in education experiments: A discussion of the issues* (NCEE 2009-013). Washington, DC: National Center for Education Evaluation and Regional Assistance, Institute of Education Sciences, U.S. Department of Education. Retrieved from http://files.eric.ed.gov/fulltext/ED511776.pdf

Mayer, D. P. (1999). Measuring instructional practice: Can policymakers trust survey data? *Educational Evaluation and Policy Analysis, 21*(1), 29-45. http://dx.doi.org/10.3102/01623737021001029

Merlino, F. J. (PI) along with Robert Boruch, Jennifer Cromley, Laura Desimone, Christine Massey, Nora S. Newcombe, Andrew C. Porter (collaborators are listed in alphabetical order). *21st Century Research and Development Center on Cogitation and Science Instruction*. IES Funding Proposal.

Miles, M. B., & Huberman, A. M. (1994). *Qualitative data analysis* (2nd ed.). Thousand Oaks, CA: Sage.

Minstrell, J. (2001). Facets of students' thinking: Designing to cross the gap from research to standards-based practice. In K. Crowley, C. D. Schunn, & T. Okada (Eds.), *Designing for science: Implications for professional, instructional, and everyday science* (pp. 415–444). Mahwah, NJ: Lawrence Erlbaum.

National Research Council. (2012). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*. Washington, DC: National Academies Press.

NGSS Lead States. (2013). *Next generation science standards: For states, by states.* Washington, DC: The National Academies Press. doi:10.17226/13165

Nowicki, B.L., Sullivan-Watts, B., Shim, M.K., Young, B., & Pockalny, R. (2013). *Factors influencing science content accuracy in elementary inquiry science lessons. Research in Science Education, 43*(3), 1135–1154. doi:10.1007/s11165-012-9303-4

Olsen, R. B., Unlu, F., Jaciw, A. P., & Price, C. (2011). Estimating the impacts of educational interventions using states tests or study-administered tests (NCEE 2012- 4016). Washington, DC: National Center for Education Evaluation and Regional Assistance, Institute of Education Sciences, U.S. Department of Education. Retrieved from http://files.eric.ed.gov/fulltext/ED524806.pdf

Parker, J., & Heywood, D. (2000). Exploring the relationship between subject knowledge and pedagogic content knowledge in primary teachers' learning about forces. *International Journal of Science Education, 22*(1), 89–111. doi:10.1080/095006900290019

Patton, M. Q. (1990). *Qualitative evaluation and research methods* (2nd ed.). Newbury Park, CA: Sage.

Penuel, W. R., Fishman, B., Yamaguchi, R., & Gallagher, L. P. (2007). What makes professional development effective? Strategies that foster curriculum implementation. *American Educational Research Journal, 44*(4), 921–958. doi:10.3102/0002831207308221

Porter, A. C., Polikoff, M. S., Barghaus, K. M., & Yang, R. (2013). Constructing aligned assessments using automated test construction. *Educational Research, 42*(8), 415-423. doi: 10.3102/0013189X13503038

Putnam, R. T., & Borko, H. (1997). Teacher learning: Implications of new views of cognition. In B. J. Biddle, T. L. Good, & I. F. Goodson (Eds.), *International handbook of teachers & teaching* (2nd ed.; pp. 1,223–1,296). Dordrecht, The Netherlands: Kluwer.

Roediger, H. L., & Karpicke, J. D. (2006). The power of testing memory: Basic research and implications for educational practice. *Perspectives on Psychological Science, 1*, 181–210. doi:10.1111/j.1745-6916.2006.00012.x

Rowan, B., Chiang, F., & Miller, R. J. (1997). Using research on employees' performance to study the effects on students' achievement. *Sociology of Education*, *70*(4), 256–284. doi:10.2307/2673267

Ryan, G. W., & Bernard, H. R. (2003). Data management and analysis methods. In N. K. Denzin & Y. S. Lincoln (Eds.), *Collecting and interpreting qualitative materials* (2nd ed.; pp. 259–309). Thousand Oaks, CA: Sage.

Sadler, P. M., Sonnert, G., Coyle, H. P., Cook-Smith, N., & Miller, J. L. (2013). The influence of teachers' knowledge on student learning in middle school physical science classrooms. *American Educational Research Journal, 50*(5), 1020–1049. doi:10.3102/0002831213477680

Santagata, R., Kersting, N., Givvin, K. B., & Stigler, J. W. (2012). Problem implementation as a lever for change: An experimental study of the effects of professional development program on students' mathematics learning. *Journal of Research on Educational Effectiveness*, *4*(1), 1–24. doi:10.1080/19345747.2010.498562

Schmidt, W. H., McKnight, C. C., & Raizen, S. A. (1997). *A splintered vision: An investigation of U.S. science and mathematics. Executive summary.* Lansing, MI: Michigan State University, U.S. National Research Center for the Third International Mathematics and Science Study.

Schwartz, D. L., & Bransford, J. D. (1998). A time for telling. *Cognition and Instruction, 16*, 475–522. doi:10.1207/s1532690xci1604_4

Scull, J., Porter, A.C., Massey, C., & Merlino, F.J. (2016). Embedding Cognitive Science Principles into Middle School Science Instruction. Working Paper. Philadelphia, PA: University of Pennsylvania.

Shallcross, T., Spink, E., Stephenson, P., & Warwick, P. (2002). How primary trainee teachers perceive the development of their own scientific knowledge: Links between confidence, content and competence? *International Journal of Science Education, 24*(12), 1293–1312. doi:10.1080/09500690110110106

Shulman, L. S. (1986). Those who understand: Knowledge growth in teaching. *Educational Researcher, 15*(2), 4–14. Retrieved from http://www.jstor.org/stable/1175860. http://dx.doi.org/10.3102/0013189X015002004

Somers, M., Zhu, P., & Wong, E. (2011). *Whether and how to use state tests to measure student achievement in a multi-state randomized experiment: An empirical assessment based on four recent evaluations* (NCEE Reference Report 2012-4015). Washington, DC: National Center for Education Evaluation and Regional Assistance, Institute of Education Sciences, U.S. Department of Education. Retrieved from http://files.eric.ed.gov/fulltext/ED524891.pdf

Spencer, K., Desimone, L., & McMaken, J. (2011). *Intervention Implementation and Classroom Instruction as a Mediating Variable in Middle School Science Achievement.* Paper Presented at the Annual Meetings of the American Education Research Association, New Orleans, LA.

Starkey, L., Yates, A., Meyer, L. H., Hall, C., Taylor, M., Stevens, S., & Toia, R. (2009). Professional development design: Embedding educational reform in New Zealand. *Teaching and Teacher Education, 25*, 181–189. doi:10.1016/j.tate.2008.08.007

Strauss, A., & Corbin, J. (1998). *Basics of qualitative research: Techniques and procedures for developing grounded theory* (2nd ed.). Thousand Oaks, CA: Sage.

Supovitz, J. A. (2001). Translating teaching practice into improved student achievement. In S. H. Fuhrman (Ed.), *From the Capitol to the classroom: Standards-based reform in the states* (pp. 81–98). Chicago, IL: University of Chicago Press.

Supovitz, J. A., & Turner, H. M. (2000). The effects of professional development on science teaching practices and classroom culture. *Journal of Research in Science Teaching, 37*(9), 963–980. doi:10.1002/1098-2736(200011)37:9<963::AID-TEA6>3.0.CO;2-0

Vosniadou, S., Skopeliti, I., & Ikospentaki, K. (2004). Modes of knowing and ways of reasoning in elementary astronomy. *Cognitive Development*, *19,* 203–222. doi:10.1016/j.cogdev.2003.12.002

Wilson, S., Floden, R., & Ferrini-Mundy, J. (2002). Teacher preparation research: An insider's view from outside. *Journal of Teacher Education, 53,* 89–122. doi:10.1177/0022487102053003002

Yang, R., Porter, A. C., Massey, C., & Merlino, F. J. (2016). Applying cognitive science principles to a traditional middle school science curriculum: comparing two approaches to increasing student achievement. Working Paper. Philadelphia, PA: University of Pennsylvania.

Yoon, K. W., Duncan, T., Wen-Yu Lee, S., Scarloss, B., & Shapley, K. L. (2007). *Reviewing the evidence on how teacher professional development affects student achievement.* Washington, DC: U.S. Department of Education, Institute of Education Sciences, National Center for Education Evaluation and Regional Assistance, Regional Educational laboratory Southwest. Retrieved from http://files.eric.ed.gov/fulltext/ED498548.pdf

Yoon, S., Liu, L., & Goh, S. (2010). Convergent adaptation in small groups: Understanding professional development activities through a complex systems lens. *Journal of Technology and Teacher Education*, *18*(2), 177–203.

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