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Research Article

Mapping Out the Integration of the Components of Pedagogical Content Knowledge (PCK): Examples From High School Biology Classrooms

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Abstract: This study explored the nature of the integration of the five components of pedagogical content knowledge (PCK): (a) Orientations toward Teaching Science, (b) Knowledge of Student Understanding, (c) Knowledge of Instructional Strategies and Representations, (d) Knowledge of Science Curriculum, and (e) Knowledge of Assessment of Science Learning. Given the topic and context specificity of PCK, this investigation was conducted in the context of the photosynthesis and heredity instruction of four teachers who were working at the same high school with the same curricular materials. Data sources included classroom observations, semi-structured interviews, lesson plans, instructional materials, and students' work samples. Data were analyzed through three different approaches: (a) in-depth analysis of explicit PCK, (b) enumerative approach, and (c) the constant comparative method. Data analysis indicated five salient features of the integration of the PCK components: (a) the integration of the components was idiosyncratic and topic-specific; (b) Knowledge of Student Understanding and Knowledge of Instructional Strategies and Representations were central in the integration; (c) Knowledge of Science Curriculum and Knowledge of Assessment of Science Learning had most limited connection with other components; (d) Knowledge of Assessment of Science Learning was more often connected with Knowledge of Student Understanding and Knowledge of Instructional Strategies and Representations than with the other components; and (e) Didactic Orientations toward Teaching Science directed Knowledge of Instructional Strategies and Representations inhibiting its connection with other components. This study highlights that the quality of PCK depends on the coherence among the components as well as the strength of individual components. From a methodological perspective, this study demonstrates the possibility to make PCK more visible and accessible by using a PCK Map, a pictorial representation of the interactions of the PCK components. © 2012 Wiley Periodicals, Inc. J Res Sci Teach 49: 922–941, 2012
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Teaching is not the simple transmission of information but a complex act that requires teachers to apply knowledge from multiple domains in order to facilitate student learning (Leinhardt & Greeno, 1986; Resnick, 1987; Wilson, Shulman, & Richert, 1987). In order to accommodate diverse interests, understanding, abilities, and experiences of students, teachers need to develop a special body of knowledge that exceeds content knowledge. Such

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knowledge enables teachers to translate content knowledge into effective teaching strategies to meet the learning needs of individual students (NRC, 1996). At the center of this type of knowledge is pedagogical content knowledge (PCK) (Shulman, 1986, 1987).

Shulman (1986, 1987) first conceptualized PCK as a special amalgam of content and pedagogy that guides "ways of representing and formulating the subject that make it comprehensible to others" (1986, p. 9). This knowledge includes understanding how particular topics, problems, or issues are organized, represented, and adapted to the diverse interests and abilities of learners, as well as how they are presented for instruction (Shulman, 1987). Since the inception of PCK, scholars have worked on the concept and consequently the concept of PCK has been interpreted in multiple ways according to different scholars and research agendas, each pointing to a different quality, characteristic, context, attribute, behavior, etc. (Park & Oliver, 2008a). In spite of the disagreement on its definition, the blending of content knowledge and pedagogical knowledge in the context of facilitating student learning is the key to conceptualizing PCK (Park & Oliver, 2008a; Van Driel, Verloop, & De Vos, 1998).

A particularly persuasive way of defining PCK is to identify central components constituting PCK based on researchers' beliefs, experiences, or empirical studies and then to describe PCK as an integration of those components. Although educational scholars have not yet fully reached a consensus on components comprising PCK, they agree that in order for teachers to effectively plan and enact instruction for a certain group of students in a particular context they should be able to integrate the components into PCK in a coherent way (Loughran, Berry, & Mulhall, 2006; Van Driel, De Jong, & Verloop, 2002). Research indicates that these components interact in highly complex ways (Park & Oliver, 2008a), and a coherent integration among them is critical to PCK development and further changes in practice (Cochran, DeRuiter, & King, 1993; Magnusson, Krajcik, & Borko, 1999).

Given the importance of the coherence among the components, many researchers have explored how the components interact with one another to shape the whole structure of PCK. However, those studies have focused on only one or two components, examining how a particular component is related to another component (e.g., Cohen & Yarden, 2009; Veal & Kubasko, 2003), or how the development of one component influences a teacher's whole PCK and practice (e.g., Kamen, 1996; Matese, 2005). Consequently, the nature and dynamics of the interaction among the components through which they are integrated into PCK have not been fully resolved.

Understanding each component in depth—independently from others—can serve as a conduit to enhance our knowledge of PCK. Given the integrative aspect and complexity of PCK, however, to provide insightful implications for practice, it is necessary to investigate how all components interact with one another and how they are integrated into PCK that enables a teacher to transform content knowledge into instructional events from a more holistic perspective. Abell (2008) argued that in order to understand the quality of PCK, researchers must attempt to understand the interaction of the PCK components in addition to examining individual components. Friedrichsen, Van Driel, and Abell (2011) also critiqued that research on the PCK of science teachers typically focus on individual PCK components paying no attention to their relation to each other. With this in mind, this study explored the nature of the interaction among different PCK components through which they are integrated into PCK that guides teacher practice. In an effort to facilitate the identification of the interaction, this study also aimed to develop an analytic tool that makes the process more visible and measurable. This study was conceptually grounded in the pentagon model, which defines PCK as an integration of five components that are mutually related to one another (Park & Oliver, 2008b). A detailed description of the pentagon model will be provided in the next section. The research question that guided this study was: What is the nature of the integration of the five PCK components that affects teaching practice in high school biology classrooms?

Theoretical Background

Conceptualization of PCK

Shulman (1986) advanced thinking about teacher knowledge by introducing the concept of PCK, acknowledging the importance of the transformation of subject matter knowledge per se into subject matter knowledge for teaching. PCK is described as a blend between content and pedagogy demonstrated by an understanding of how to translate subject matter knowledge into "forms that are pedagogically powerful and yet adaptive to the variation in ability and background presented by the students" (Shulman, 1987, p. 15). This knowledge distinguishes a science teacher from a scientist since it lies at the intersection of content and pedagogy, including knowing which aspects of the content students can learn at a particular developmental stage, how to present it to them, and how to lead them into different conceptual understandings (Loucks-Horsley, Hewson, Love, & Stiles, 1998; Loughran, Mulhall, & Berry, 2004).

Shulman's introduction of PCK has inspired numerous responses among educational scholars, resulting in various models of PCK (Appleton, 2003; Friedrichsen et al., 2009; Hashweh, 2005; Magnusson et al., 1999; Park & Oliver, 2008a). PCK models differ in their conceptualizations of the relationship between Subject Matter Knowledge (SMK) and PCK (Kind, 2009). For example, while Grossman (1990) and Magnusson et al. (1999) regarded SMK and PCK as separate knowledge bases for teaching, Marks (1990) and Fernandez-Balboa and Stiehl (1995) included SMK within PCK. Regardless of those different views, one common feature of the PCK models is that they elaborated and expanded on Shulman's concept (1986, 1987) by modifying the constituent components or adding new components based on empirical evidence or researchers' beliefs (Kind, 2009). This approach is grounded in the conception that PCK is a synthesis of the components constituting PCK (Abell, 2008; Lee & Luft, 2008). In this regard, the level of a teacher's PCK depends on the degree of the integration and coherence among the components as well as the possession of individual components (Friedrichsen et al., 2009; Krauss et al., 2008; Park & Oliver, 2008a).

Considering the importance of interrelatedness among the components in understanding the construct of PCK, this study employed the pentagon model of PCK (Park & Oliver, 2008b) as a conceptual framework since the model underscores the coherent nature of the PCK components (see Figure 1). The pentagon model was first constructed through a comprehensive literature review and then elaborated through empirical tests against the model (Park & Oliver, 2008a, 2008b). In particular, this model was largely drawn from the work of Grossman (1990), Tamir (1988), and Magnusson et al. (1999). Grossman's four knowledge domains for teaching (i.e., Pedagogical Knowledge (PK), PCK, SMK, and Knowledge of Context) provided a theoretical foundation that helped conceptualize PCK in relation to other teacher knowledge domains in developing the pentagon model. By adopting Grossman's ideas, PCK is defined as a special domain of knowledge produced by the transformation of other knowledge domains for creating effective learning opportunities (Gess-Newsome, 1999). Although PCK is conceptualized as a separate knowledge domain alongside other knowledge domains, it is not "a free-standing type of knowledge" (Abell, 2008, p. 1409) in that it is continuously influenced by and influences the others (Magnusson et al., 1999). Defining PCK as the transformation of the other knowledge domains and considering their reciprocal and nurturing relationship with PCK (Gess-Newsome, 1999), these parent domains

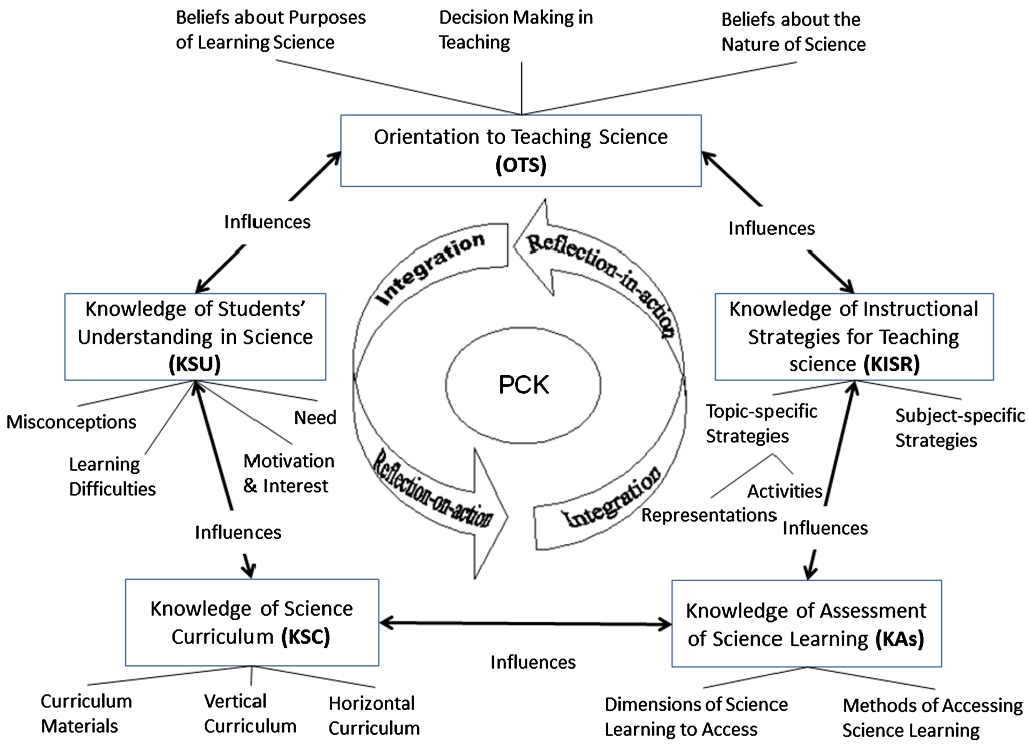


Figure 1. Pentagon model of PCK for teaching science (modified from Park & Oliver, 2008b by rearranging the components and adding their abbreviations).

such as SMK and PK are inevitably embedded into PCK. Although PK, SMK, PCK, and Knowledge of Context are conceptualized as discrete knowledge domains for teaching, it does not mean that teacher knowledge is organized into those isolated categories (Grossman, 1990). Rather, those categories are to be used as "a heuristic devise for helping us think about teacher knowledge" (Borko & Putnam, 1996, p. 677).

With the conceptualization of the four knowledge domains for teaching discussed above, PCK is then defined as an integration of five components represented in the pentagon model: (a) Orientations toward Teaching Science (OTS), (b) Knowledge of Students' Understanding in Science (KSU), (c) Knowledge of Science Curriculum (KSC), (d) Knowledge of Instructional Strategies and Representations (KISR), and (e) Knowledge of Assessment of Science Learning (KAs) (see Park & Oliver, 2008a for descriptions of the five components). As a matter of fact, Magnusson et al. (1999) represented the same five components in their PCK model as the pentagon model. Although Magnusson et al. acknowledged the importance of the interaction and coherence among the components, their PCK model did not reflect this notion. In their model, the five components were presented in a linear way that emphasized the interaction only between Orientations to Teaching Science and each of the other four components and consequently ignored the interaction among the four components (Friedrichsen et al., 2011). On the other hand, the pentagon model presents the components in a pentagonal form to emphasize the interrelatedness among them putting equal weight on each interaction as shown in Figure 1.

This model implies that PCK for effective teaching requires the integration of the components in complicated ways so that lack of coherence among the components can be problematic in developing PCK. In other words, strong PCK has all components connected to each other strongly enough to enable the whole structure of PCK to function for scaffolding student learning. In this regard, an increase in a single component without a corresponding increase in the others may not be sufficient to change the whole PCK structure to stimulate changes in practice (Park & Oliver, 2008a). The integration among the components is accomplished in a way that strengthens the coherence among the components through complementary and ongoing readjustment motivated by both reflection-in-action and reflection-on-action (Nilsson, 2008; Park & Oliver, 2008b). The pentagon model served as both the conceptual and analytic frameworks for this study.

Research on the Interconnectedness and Integration Among the PCK Components

Research on comparing the knowledge bases of expert and novice teachers suggests that expert teachers' knowledge bases are not only more extensive than those of novice teachers but also differently structured in more highly connected and integrated modes (Berliner, 2001; Meijer, Verloop, & Beijaard, 1999). A quantitative study by Krauss et al. (2008), which examined the content knowledge and PCK of 198 mathematics teachers, highlighted the notion that mathematical expertise depends on the degree of connectedness between the two knowledge bases. Friedrichsen et al. (2009) explored the relation between teaching experience and PCK and found that teaching experience plays a critical role in PCK development by facilitating more integration among the PCK components.

Studies to understand the integration of PCK components have been conducted mainly by two approaches. The first approach explores how a single component affects another component. For example, Cohen and Yarden's research (2009) indicated that teachers' lack of curricular knowledge of the topic of cells limited their use of instructional strategies while Veal and Kubasko's research (2003) demonstrated how different epistemological orientations between biology and geology teachers impacted their different approaches to teaching evolution. Similarly, Brown, Friedrichsen, and Abell (2009) and De Jong, Van Driel, and Verloop (2005) investigated the relation between knowledge of student understanding and knowledge of instructional strategies without addressing other components of PCK.

The other approach examines how a particular component is related to the whole construct of PCK and practice. For example, the studies conducted by Clermont, Krajcik, and Borko (1993) and Van Driel et al. (1998) indicated that teachers' knowledge of student understanding such as preconceptions, learning difficulties, and reasoning types in a specific domain facilitated their PCK development. In a similar vein, Kamen (1996) and Matese (2005) argued that teachers' knowledge of assessment significantly influenced their knowledge for teaching and practice.

These previous studies opened a fruitful avenue of exploration toward a deep understanding of how one component relates to another component, to the whole PCK, and further to practice. However, little attention was paid to how individual components are connected with others in a way that organizes, develops, and validates PCK. Hashweh (2005) argued that "PCK does not result from deep knowledge in a single knowledge category" (p. 279). We need to "understand how they [the components] interact and how their interaction influences teaching" (Magnusson et al., 1999, p. 115). A better understanding of this interaction process of the PCK components from a holistic point of view will help explain relationships among the components which will provide insights into the nature of the PCK development. This understanding will also contribute to designing teacher education programs including program structure and course assignments to best support teachers' PCK development which will promote student learning. In addition, investigating the PCK construct in terms of the interactions of its constituting components beyond its composition will encourage a new perspective on what specifies teaching expertise and what makes differences in knowledge bases and practice between expert and novice teachers.

Methods

Research Design

This study employed a "basic qualitative study design" (Merriam, 1998, p. 11). Participants were four high school biology teachers working in a high school in Midwest America. Table 1 presents background information of the participants. For confidentiality, all were given pseudonyms. While Sandy is Asian-American, the others are Caucasians. All four teachers earned Master's degrees in either education or science and their teaching experience ranged from 2 to 43 years. Although the purpose of this study is to better understand the integration of the PCK components, given the topic- and context-specificity of PCK (Baxter & Lederman, 1999), the investigation focused on the topics of photosynthesis and heredity taught by the four teachers who were working at the same high school with the same curricular materials.

Table 1
Background information of participants

Name	Sandy	Antonia	Bruce	David
Gender	Female	Female	Male	Male
Education	B.S./M.Ed	B.S./M.Ed	B.S./M.Ed	B.S./M.S.
Science Background	Biology	Biology	Biology	Biology
Teaching Subject	General Biology	General Biology	General Biology	AP Biology
Teaching Years	2	4	14	43

Data Collection

Major data sources included non-participant classroom observations, semi-structured interviews, lesson plans, instructional materials, and students' work samples. Classroom observations were made in the three sections of General Biology taught by Sandy, Antonia, and Bruce respectively and an Advanced Placement (AP) Biology class taught by David. General Biology is an introductory course for students in grades 10, 11, and 12 (i.e., student age ranges from 15 to 18) who completed the prerequisite course, Foundations of Science in grade 9 (i.e., student age ranges from 14 to 15). AP Biology is an advanced biology course designed to be the equivalent of a college introductory biology course usually taken by biology majors during their first year. Any high school student can take the AP biology course after the successful completion of a first course in high school biology (e.g., Foundations of Science in this school) and one in high school chemistry. Students who obtained high enough scores on the AP biology exam can earn college credit for the introductory biology course at participating colleges. All AP courses are sponsored by the College Board in the US.

Although all instructional sessions of the two topics were videotaped (five class periods for photosynthesis and eight class periods for heredity for each teacher on average), two class periods on each topic for each teacher were selected for the purpose of this study in which all four teachers dealt with the same subject matter in a similar way (i.e., lab and whole group discussion). Each of the class periods selected for this study was 50-minute long with an average class size of 20.

Given that observation can provide only limited insight into a teacher's PCK, three different types of semi-structured interviews were carried out to understand what teachers know and the reason for their instructional actions: (a) background interview, (b) pre-observation interview, and (c) post-observation interview. In the background interview, participants were asked questions related to their teaching backgrounds, orientations to science teaching, and knowledge of teaching photosynthesis and heredity. This interview lasted approximately 30 minutes to 1 hour for each teacher. Because PCK appears in the planning, interactive, and post-active of teaching (Hashweh, 2005), the pre-observation and post-observation interviews were conducted in combination with each observation. The pre-observation interviews focused on teachers' planning of the lesson to be observed such as the objectives of the lesson, what they took into consideration in planning it, assessment plan, etc. After each observation, a post-observation interview was conducted to understand each teacher's reflection on the lesson, especially his/her thoughts on several interesting classroom incidents noted by the observer. In participating in the interview, the teachers had opportunities to revisit the lesson and to articulate the reasons for their instructional decisions. Specific interview questions are provided in Supporting Information Appendix A. All interviews were audio-taped and transcribed verbatim.

Documents—including lesson plans, handouts, and students' work samples—were also included as data sources. Students' work samples consisted of lab reports, notes, written assignments, and posters for classroom presentations. Handouts included instructional supplies that the teachers provided to students and assessment materials.

Data Analysis

In order to capture the nature and dynamics of the integration process of the PCK components, data were analyzed through three approaches: (a) in-depth analysis of explicit PCK (Park & Oliver, 2008a), (b) enumerative approach (LeCompte & Preissle, 1993), and (c) the constant comparative methods (Strauss & Corbin, 1990). What follows is the description of each analysis approach.

In-Depth Analysis of Explicit PCK. In order to identify components integrated into a teacher's PCK in a specific teaching segment, we utilized a modified form of the in-depth analysis of explicit PCK (Park & Oliver, 2008a). In this approach, we first identified teaching segments from videotaped instructional sessions that revealed a teacher's PCK according to our operational definition of PCK, that is, PCK as an integration of two or more components in the pentagon model. Once a teaching segment that indicated the presence of two or more components of PCK was identified (hereafter called "PCK Episode"), a detailed description of the PCK Episode was composed in terms of: (a) what the teacher and students did, (b) what components of PCK were integrated in the PCK Episode, and (c) evidence of the presence of the components identified (see Supporting Information Appendix B for an example). The description was derived mainly from observations but complemented by interviews and documents related to the teaching segment. When we identified components integrated into a particular PCK Episode, our focus was not how many times a particular component appears but whether the component is present or not in the Episode. In other words, we did not count the occurrence of a component but we looked for occurrence of the component at least once in the Episode. Table 2 shows the number of PCK Episodes identified in each instructional session of each teacher. The length of the PCK Episodes ranges between 1 minute (e.g., questions and answers during a short discussion) and 30 minutes (e.g., experiment).

Table 2
Number of PCK Episodes identified in each instructional session of each teacher

Topics	Instructional Sessions	Teachers			
		Sandy	Antonia	Bruce	David
Photosynthesis	I (Lab)	4	7	6	2
	II (Whole group discussion)	6	5	10	5
Total		10	12	16	7
Heredity	I (Lab)	4	3	2	2
	II (Whole group discussion)	2	3	6	3
Total		6	6	8	5

Enumerative Approach. In order to portray the integration process of the PCK components in a clear and explicit way, an enumerative approach was employed (LeCompte & Preissle, 1993). Once PCK components integrated in a particular PCK Episode were identified through the in-depth analysis of explicit PCK described before, we indicated the connections among the components using the pentagon model as an analytic device (we call this a PCK Map) with the assumption that there must be at least one connection between any two of the identified components in a special way. For example, if OTS, KSC, and KAs were recognized as working components in a particular PCK Episode, one connection was recorded between any two of the three as depicted in Figure 2. Although the strength of one connection might be different from another, we assumed the same strength of 1 for each connection for analytic convenience. In other words, even though individual connections between component pairs may differ in strength, each has been given "1."

The same procedure was repeated for the other PCK Episodes in the given instructional session. Next, the frequency of the connection between any two components was summed up across all PCK Episodes in the instructional session and it was indicated in the analytic device, that is, PCK Map. Figure 3 shows Sandy's PCK Map for an instructional session (whole group discussion session) of photosynthesis. This PCK Map indicates that six PCK Episodes were identified in this instructional session (i.e., E1–E6), and the connection

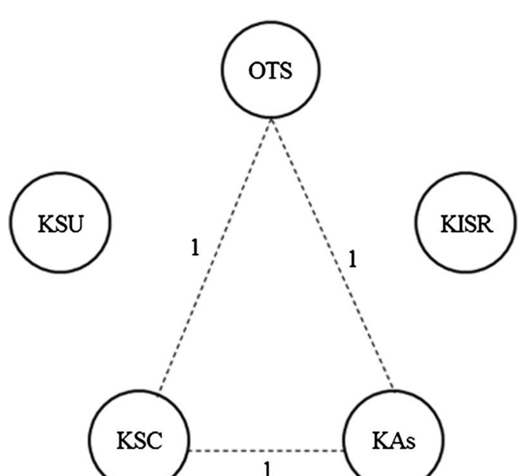


Figure 2. Example of the first step of the enumerative approach.

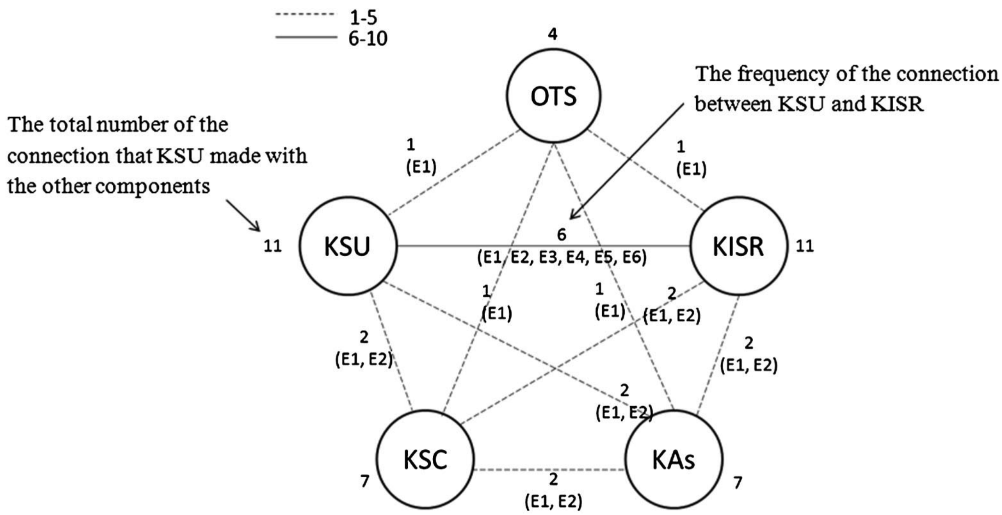


Figure 3. Sandy's PCK map for an instructional session of photosynthesis.

between KSU and KISR was identified in all of the six Episodes, while the connection between KSC and KAs was identified in only two (i.e., E1 and E2). The number beside each component designates how many times the component was connected with other components in the instructional session.

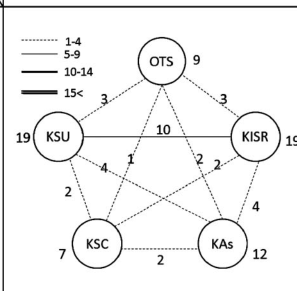
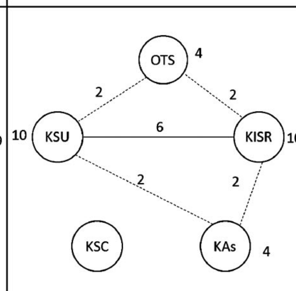
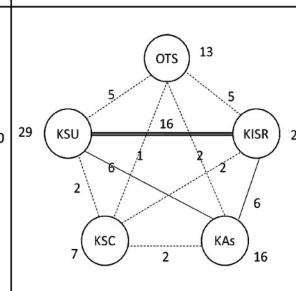
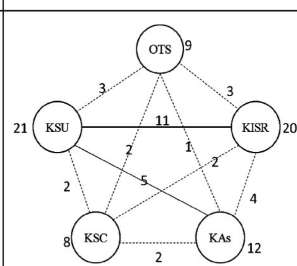
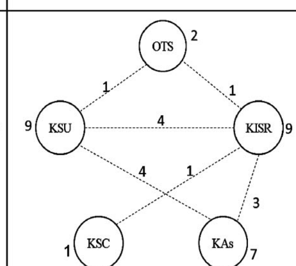
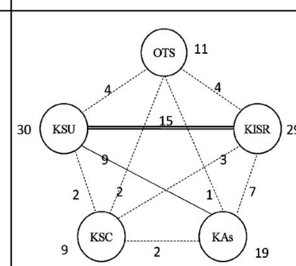
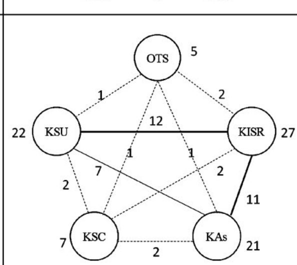
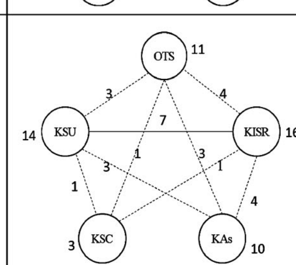
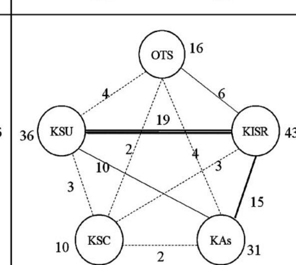
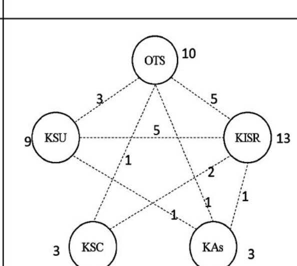
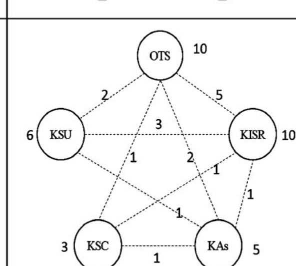
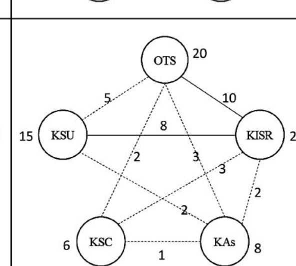
The Constant Comparative Method. In this approach, the data analysis focused on the identification of common patterns that emerged from the data, especially interviews and observations, in terms of the nature of the integration of the components without using a pre-established system of categories or codes. The results from the constant comparative method were compared and contrasted to those from PCK Maps created through the in-depth analysis of explicit PCK and enumerative approach in order to provide methodological triangulation (Denzin, 1978).

Results

The teachers' PCK Maps for each topic are summarized in Table 3. Each teacher's PCK Maps for the two topics were compiled into a total PCK Map. In a PCK Map, the frequency of each connection also indicates the strength of the connection since each connection is given "1" for its strength. As the frequency of a connection is higher, the connection is stronger.

Our close analysis of the PCK Maps and the patterns that emerged through the constant comparative method indicated five salient features of the integration of the PCK components: (a) the integration of the components was idiosyncratic and topic-specific; (b) Knowledge of Student Understanding (KSU) and Knowledge of Instructional Strategies and Representations (KISR) were central in the integration; (c) Knowledge of Science Curriculum (KSC) had the most limited connection with other components; (d) Knowledge of Assessment (KAs) was more often connected with KSU and KISR than Orientations toward Teaching Science (OTS) and KSC; and (e) Didactic OTS directed KISR inhibiting its connection with other components.

Table 3
PCK maps for photosynthesis and heredity

Topic / Teacher	Photosynthesis (2 Instructional Sessions)	Heredity (2 Instructional Sessions)	Total (4 Instructional Sessions)
Sandy			
Antonia			
Bruce			
David			

The Integration of the Components Was Idiosyncratic and Topic-Specific

As shown in Table 3, even though the teachers taught the same topic with the same instructional materials and similar lesson plans, their PCK Maps differed to a certain degree. Furthermore, even an individual teacher's PCK Map differed for different topics. In particular, Sandy, Antonia, and Bruce demonstrated more coherently structured PCK Maps for photosynthesis than heredity. For example, Bruce integrated the components of KSU, KISR, KAs, and KSC 22, 27, 21, and 7 times, respectively, while teaching photosynthesis; but he only integrated the same components 14, 16, 10, and 3 times, respectively, while teaching heredity. During interviews, Bruce often confessed that teaching heredity is more challenging to him than teaching photosynthesis because there are too many concepts he needs to cover and he is not quite sure how to effectively incorporate those concepts into his teaching strategies. Consistent with this confession, his photosynthesis classes placed more emphasis on problem-solving than the transmission of content knowledge using inquiry-based teaching approaches (Field notes, April 29, 2008). In his class on photosynthesis, students were engaged in activities in which they made observations, gathered data, interpreted data as results, and compared those results with scientific concepts as Bruce described:

> They had some background of what photosynthesis basically was but they still didn't have the full story ... so this was a way to have them conduct an experiment ... just like a scientist in a lab ... they're gathering data, and then they have to assess the data, they were going through that process. (Bruce, Post-observation interview #3)

In contrast, Bruce's heredity unit focused on the memorization of concepts and facts. Although there were experiments in the heredity unit, most were cookbook type activities. For example, during the class on DNA, he asked students to construct a strand of DNA using four different colors of beads following the rule he gave to them. Accordingly, his heredity PCK Maps show less connections among the components, especially fewer connections between Knowledge of Student Understanding and Knowledge of Instructional Strategies and Representations, than his photosynthesis PCK Maps show.

The idiosyncratic nature and topic-specificity of PCK have been either conceptually or empirically advocated by many scholars (e.g., Grossman, 1990; Loughran, Mulhall, & Berry, 2008; Park & Oliver, 2008a; Van Driel et al., 1998). Our findings suggest, however, that those features are not only derived from different PCK components involved in a teaching episode but also different integration dynamics among the components.

KSU and KISR Were Central in the Integration

Another common pattern across the teachers' PCK Maps was that Knowledge of Student Understanding (KSU) and Knowledge of Instructional Strategies and Representations (KISR) were the most frequently integrated with any other component. In addition, the connection between those two components was the strongest among all connections in all PCK Maps except for David's (e.g., Sandy: 16; Antonia: 15; Bruce: 19 connections. Since the same strength of one was assigned to each connection between two components, the frequency of the connection indicates its strength). This implies that the teachers' understanding of student understanding (KSU) and corresponding teaching strategies (KISR) mainly guided what other components needed to be incorporated in what ways and consequently shaped their PCK Map.

Given that teachers ought to know what students already know and what they are likely to have difficulty in learning a particular topic in order to generate appropriate representations and teaching strategies, the strong connection between KSU and KISR seems natural. This connection often appeared in the teachers' instruction. For instance, after a laboratory activity on the rate of photosynthesis, Antonia became aware that some students developed a misconception that the rate of photosynthesis was higher under green light than under red or blue light. She said, "They have some misconceptions about light and wave lengths of light and that's difficult at their age" (Antonia, post-observation interview #4). With this understanding, she came to redesign the next class to "show them some other data [including wavelength of light, rate of photosynthesis, and absorbance of chlorophyll] ... so that they could see how it works with the different colors of light" (Antonia, pre-observation interview #5).

However, it was also the case that when the teachers identified student learning difficulties or misconceptions, they sometimes did not attempt to tailor their instructional strategies to meet the students' learning needs or to confront their misconceptions. In other words, teachers' knowledge of student understanding (KSU) was not always connected to their knowledge of instructional strategies and representations (KISR). For example, in Sandy's heredity unit, she recognized that the DNA replication process was too abstract for her students to understand even after watching a video of the procedure. But, she did not endeavor to figure out how she could help them better understand it. This aspect was reflected in her PCK Map for heredity. In her heredity Map, KSU was identified 10 times, but only 6 of the 10 were connected with KISR.

KSC Had Most Limited Connection With Other Components

The PCK Maps indicated that the four teachers rarely integrated Knowledge of Science Curriculum (KSC) into their PCK. In particular, as shown in Table 3, KSC had the fewest and therefore weakest connections with other components across the four teachers (i.e., in the total PCK Maps, Sandy, Antonia, Bruce, and David integrated KSC 7, 9, 10, and 6 times, respectively). Knowledge of Science Curriculum refers to teachers' understanding of both the horizontal and vertical curricula for a subject and curriculum materials available for teaching a particular subject matter (Grossman, 1990). Knowledge about the horizontal curricula is demonstrated by teachers' knowledge of the goals and objectives for students in the subject they are teaching (e.g., state and national standards) as well as the articulation of those guidelines across topics addressed during the school year (Magnusson et al., 1999). Knowledge about what students have learned in previous years and what they are expected to learn in later years is included in teachers' knowledge about the vertical curriculum (Grossman, 1990).

Data analysis using the constant comparative method revealed that the teachers' knowledge of the national, state, or local standards for the topics taught during the school year was rarely integrated into PCK that affected their instructional decisions. For example, David often exhibited his knowledge of National Science Education Standards (NRC, 1996) and curriculum guidelines, but he did not use this knowledge much as a referent to figure out how to construct a lesson to best support student learning. He perceived the national standards as a collection of topics to be taught and regarded covering the topics as meeting the standards as implied in his statement, "Genetics is covered in the national standards. Although it's not real clear about what it is, what you're to do with it, it's in there. And I'm teaching genetics" (David, General interview #2). Consequently, he did not use the national standards as a filter through which he made decisions on the importance of various topics relative to the curriculum as a whole in designing, enacting, and revamping his instruction. Overall, David's case indicated that knowing what the curriculum is differs from knowing how to teach with it.

Although the connection of Knowledge of Science Curriculum (KSC) with other components occurred the fewest times, it was connected more frequently with Knowledge of Instructional Strategies and Representations (KISR) than with any other component. For example, in Bruce's photosynthesis unit, he strove to find ways to synthesize four experiments on the rate of photosynthesis in the textbook into one experiment because he thought that one experiment would constitute an adequate time allotment to the core concepts in the topic. He said,

> Conducting the four experiments and getting the results would take an awful lot of our time in the curriculum and we have many other things that we would like to do. So I spent a couple of days looking at this and putting the questions together and figuring out what I wanted to do with it. (Bruce, post observation interview #4)

KSC enables teachers to differentiate between big ideas and trivial facts in relation to the curriculum in unison, which leads them to modify activities included in reference materials and eliminate ones they judged to be tangential to the understanding of the big ideas (Friedrichsen et al., 2009; Geddis, Onslow, Beynon, & Oesch, 1993). In this regard, the close connection between KSC and KISR seems reasonable.

KAs Was More Often Connected With KSU and KISR Than With the Other Components

Knowledge of Assessment (KAs) was the third most frequently integrated component after Knowledge of Student Understanding (KSU) and Knowledge of Instructional Strategies and Representations (KISR) in the total PCK Maps. This component consists of knowledge of the dimensions of science learning that are important to assess within a particular unit of study and knowledge of the methods by which that learning can be assessed (Tamir, 1988). Teachers' knowledge of methods of assessment includes knowledge of specific instruments, approaches, or activities that can be used during a particular unit of study to assess important dimensions of science learning (Magnusson et al., 1999).

The teachers often applied different questioning skills to diagnose their students' level of understanding of the concept being taught and furthermore to tailor instruction accordingly. Consequently, the teachers' Knowledge of Assessment (KAs) frequently made connections with KSU and KISR. For example, Sandy tended to ask a series of similar questions related to a particular concept at the beginning of each class. She believed that before teaching a concept, she should uncover her students' initial level of understanding of the concept and that an effective way to assess their current understanding is to ask questions. She said,

> Asking questions on a target concept over and over is what I like to do for my diagnostic assessment. The kids are all coming at me at different rates of learning, different understanding so the more repetition I do and they do, I see what they know and what they don't know. If they don't understand what a chromosome is, how can I explain what meiosis is? (Sandy, post observation interview #1)

In a similar vein, Bruce administered a pretest to assess students' initial understanding and used the information from the test to adapt his instruction. This feature is summarized in the statement below:

> I evaluated pretests and it seems ... an idea of blending or dominate, incomplete dominate, and multiple allele traits ... those are challenging to them ... they are still stuck on either it is black or white ... That's probably the biggest misconception that I need

> to work on through examples, videos, and problem-based approaches. (Bruce, pre-observation interview #5)

Both examples highlight that the teachers' knowledge of the formative assessment enabled them to gauge where their students are in learning a particular science concept through which they further improved their Knowledge of Student Understanding (KSU). With the new knowledge of student understanding drawn from the formative assessment, the teachers came up with new approaches to better scaffold student understanding through which they expanded their repertoire of instructional strategies and representations.

Didactic OTS Directed KISR Inhibiting Its Connection With Other Components

As briefly mentioned in the previous sections, David's case often appeared as a contradiction that did not support patterns or explanations that emerged from the analysis of the other teachers (Creswell, 1998; Patton, 2001). David's PCK Maps did not fit within the first two findings discussed before: (a) topic-specific integration of the components, and (b) strong connection between Knowledge of Student Understanding (KSU) and Instructional Strategies and Representations (KISR). His PCK Maps were similar between the two topics in terms of the number and strength of the connections among the components so that they did not demonstrate topic-specificity. While the connection between KSU and KISR was strongest in the other teachers' PCK Maps, the connection between Orientations toward Teaching Science (OTS) and KISR was strongest in David's. This recognition led to an in-depth analysis of the data collected from David using the constant comparative method (Strauss & Corbin, 1990) to develop a richer and fuller understanding of the interaction among the PCK components in his PCK Maps. As a result, it emerged that his OTS significantly regulated KISR and prevented the connection of KISR with other components, especially with KSU.

Orientations toward teaching science (OTS) refer to a teacher's "way of viewing and conceptualizing science teaching" (Magnusson et al., 1999, p. 97). OTS consist of three dimensions: teachers' beliefs about the goals of teaching science, beliefs about the nature of science, and beliefs about science teaching and learning (Friedrichsen et al., 2011). When Friedrichsen's (2002) two main categories of science teaching orientations (i.e., (a) teacher-centered orientations and (b) orientations based on reform efforts and associated curriculum projects) were employed to identify each teacher's orientation, it appeared that only David held teacher-centered orientation. In particular, among the nine orientations identified by Magnusson et al. (1999), David held a strong didactic orientation. In contrast, the other three teachers held orientations based on reform efforts and associated curriculum projects. In terms of Magnusson et al.'s classification, Bruce held a conceptual-change orientation and both Antonia and Sandy held a guided-inquiry orientation.

David's major goal for teaching science was to "provide students with a body of knowledge in science that we've discovered" (David, general interview #1). To achieve this goal, he presented information mainly through didactic lecture and discussion, as evident in his statement,

> They [students] don't have any knowledge, so you have to let them read and give them some content and discuss with them and talk about the content and then they can now go and carry out an experiment about that (David, post observation interview #2).

As this passage implies, even though David sometimes used laboratory work, the purpose of employing it was to have students verify science concepts taught through lecture by conducting experiments structured to "demonstrate the relationship between particular concepts and phenomena'' (Magnusson et al., 1999, p. 101). To this end, when students conducted an experiment, he usually provided a lab protocol that they had to follow.

David perceived that a student's biology learning depends upon his/her memory recall ability in terms of biology concepts and terminology. He believed that the repetition of the material and direct explanation of specific content should be an effective way to facilitate student learning. This view is reflected in the interview excerpt below:

> David: I think you [a student] eventually get it if you keep hearing it and studying it enough . . . In some cases there's just no substitute for good, old drill and practice and memorization of terms and words, and it's just that it becomes part of their vocabulary.
> Interviewer: How do you have students to learn the difficult concepts?
> David: We just have to keep repeating it over again. We repeat it as we go through it in discussion and lecture and lab summary.

It appeared that his preference for didactic teaching approaches was closely related to his view of students and their learning. He regarded students as *tabula rasa* that can be filled with knowledge transmitted from the teacher. He held the ''all-or-none'' view on student conceptual understanding. If his students appear to have misconceptions, this is because either they forget the material they learned previously or they are not exposed to that content material yet. He put it in this way:

> I'm not so sure that many of the kids are always coming in with misconceptions, but probably—they're coming in more with just a plain, flat out lack in experience or knowledge of the topic . . . They just probably don't have the knowledge sometimes or they don't remember . . . I think they eventually get it if they keep hearing it and studying it enough. (David, post observation # 1)

This perspective seems logically consistent with his beliefs about repeating information until his students have received the correct form of the information.

Taken together, his strong didactic orientation to teaching science directly shaped his teaching approaches in a way congruent with this orientation. The powerful link between OTS and KISR resulted in less room for the other components to influence his decisions on instructional strategies and representations. In particular, his disbelief in students' misconceptions impeded the connection between Knowledge of Student Understanding and Knowledge of Instructional Strategies and Representations, which was significant in the other teachers' PCK Maps. As a result, David's PCK Maps revealed the fewest connections and least coherence among the components, regardless of the topic, compared to the other teachers.

Discussion and Implications

This study examined the nature of the process through which the five constituent components were integrated into PCK that shaped the practice of four teachers working at the same high school. The findings of the study expanded the scholarship of PCK research by adding empirical evidences or new understandings to the previous literature. First of all, this study provided empirical support for the topic-specificity of PCK, which has been agreement among the researchers in the field of PCK. Grossman (1990) conceptualized PCK as ''a topic-specific integration'' of the constituent components emphasizing the topic-specific nature of PCK. In a similar vein, based on their empirical research results, Van Driel et al. (1998) argued that ''the value of PCK lies essentially in its relation with respect to specific topics'' (p. 691). Although much research indicates the topic-specificity of PCK, little is known about what contributes to this nature. The findings of this study suggested that the topic-specificity depends not only on which components constitute a teacher's PCK for a particular topic but also on how and to what degree those components interact with one another. This implies that PCK is more than the sum of the constituent components and that the synergistic interplay among the components besides the amount of knowledge in individual components contributes to the quality of PCK (Abell, 2008).

Shulman (1986) conceptualized Knowledge of Student Understanding (KSU) and Knowledge of Instructional Strategies and Representations (KISR) as key components of PCK, and most scholars have agreed with it even though their definitions of PCK vary (Park & Oliver, 2008a). This present study also empirically supported the assertion by showing that those two components are critical in shaping the structure of a teacher's PCK. In this study, KSU and KISR accounted for the most connections with other components and the connection between the two was the strongest one among all connections. Furthermore, the stronger the connection between the two components, the more stable and more coherent the structure of a PCK Map was. In sum, both KSU and KISR critically impacted the interplay among the components and consequently determined their coherence. This suggests that in order to support teachers' PCK development, each of KSU and KISR and their relationship should be target areas for improvement. For example, teachers should be given opportunities to analyze students' misconceptions and difficulties in learning a particular topic and then to connect the analysis results to practice. This suggestion has been also supported by other empirical studies (e.g., Clermont, Borko, & Krajcik, 1994; Van Driel et al., 1998).

As shown in David' case, however, when a teacher held a strong didactic orientation toward teaching science, that orientation significantly controlled KISR and consequently isolated KISR which prevented it from interacting with other components. In contrast, when a teacher's orientation was aligned with reform efforts grounded in the main idea of constructivism—that is, knowledge is not transmitted to, but constructed by, students—KISR made the strongest connection with KSU as evident in the other teachers' cases (i.e., conceptual change for Bruce; guided inquiry for Sandy and Antonia). This finding is significant in that it provides empirical evidence that explains the relationship between orientations and the other PCK components. Despite the research-supported notion of science teaching orientations as "filtering and shaping the content and development of the other PCK components" (Friedrichsen et al., 2011, p. 370), very few empirical studies have investigated interactions between orientations and other PCK components. Given the significant role of the science teaching orientation as a "conceptual map" (Grossman, 1990, p. 86) with which teachers make instructional decisions about lesson objectives, teaching strategies, the selection of curricular materials, the content and methods of student assessment, and student assignments (Borko & Putnam, 1996), more empirical studies are needed to understand science teaching orientations in relation to other PCK components and to the whole construct of PCK in the context of teaching practice.

Another salient pattern in the synthesis of the PCK components was that Knowledge of Science Curriculum (KSC) had the most limited connection with other components. This finding is inconsistent with the study of Arzi and White (2007) that examined change in secondary science teachers' subject matter knowledge through 17 years. They found that the required school science curriculum was "the single most powerful determinant of teacher knowledge, serving as both its organizer and source" (p. 221). It is not certain why this particular group of teachers in this study rarely incorporated their understanding of science curriculum into PCK in contrast to the teachers in Arzi and White (2007) since it is beyond the scope of this study. One plausible explanation that emerged from the data was that it is because the teachers in this study had a narrow view of curriculum as a collection of topics to be taught. Due to this narrow view, they used the curriculum mostly to select the topics to be covered at the beginning of a year and hardly referred to the scope and sequence of the curriculum within a grade and across grades when they designed daily lessons. However, given the contradictory research results, teachers' knowledge of science curriculum needs to be explored more directly in relation to other teacher knowledge domains.

Similarly, Knowledge of Assessment (KAs) was infrequently incorporated into the teachers' PCK. However, when it was integrated, it was usually connected with Knowledge of Instructional Strategies and Representations (KISR) and Knowledge of Student Understanding (KSU). This connection suggests that when the teachers took assessment into consideration, they were likely to align the assessment with student learning and instructional approaches, which are critical aspects of effective teaching (NRC, 1996). Given that KSU and KISR made more connections with other components, a logical inference would be that an increase in KAs will stimulate its connection with KSU and KISR and which will in turn spark a strong connectedness and coherence among the PCK components. Considering the importance of KAs in the interplay among the PCK components, more research efforts should be made to examine how KAs is synthesized into PCK and how to improve KAs itself and its connections with other components. A similar research endeavor should be also made for Knowledge of Science Curriculum (KSC) given that KSC and KAs are areas in which little research has been conducted (Abell, 2007; Davis, Petish, & Smithey, 2006).

Beyond its theoretical and empirical contributions, this study made an addition to methodology for examining PCK by demonstrating the possibility of using PCK Maps as a tool to make PCK more visible, explicit, and accessible. Various methodological attempts have been made to portray the complex construct of PCK, and most of them rely on qualitative methods which are primarily descriptive in nature (Abell, 2008). For example, Loughran et al. (2006, 2008) developed an approach called "Content Representation (CoRe) and Pedagogical and Professional experience Repertoires (PaP-eRs)" to delineate science teachers' PCK. Research has supported CoRe and PaP-eRs as a useful methodological tool not only to capture teachers' PCK, which is often tacit, but also to facilitate their reflection on practice and, moreover, professional development (Garritz, Porro, Rembado, & Trinidad, 2005; Loughran et al., 2006, 2008). However, since this approach includes detailed narrative techniques, it requires significant amounts of time for teachers to construct CoRe and PaP-eRs and for researchers to analyze them.

With this issue, the PCK Map approach was developed with the aim to make PCK more visible and clearer through quantification and visualization of PCK. This study indicated that the use of a PCK Map can open a door into exploring various research questions about PCK that remain unresolved due to the lack of appropriate methodological approaches. For example, Abell (2008) pointed out the need for research on why some particular topics are more difficult to teach than other topics for some teachers. She further suggested that this issue needs to be examined in relation to PCK. Employing the PCK Map approach will make it possible to identify the components that teachers commonly lack or they possess but often have difficulty connecting with other components for a particular topic. This understanding will help us understand how PCK is structured for teaching different topics within the same discipline. In addition, PCK Maps can be used to explore how PCK is different for beginning versus veteran teachers which will provide significant implications for teacher education. Besides its use for research purposes, a PCK Map can be used as a reflection tool for teachers assisting them in identifying which components and connections they need to improve for teaching a particular topic more effectively.

We have to admit that we created the PCK Map approach at the risk of oversimplifying the complex construct of PCK, especially in that we simply assumed one connection between any two components identified in a PCK Episode and the same degree of strength for each of the connections (i.e., 1 for each connection). However, considering the potential benefit of making PCK more accessible to theoretical and empirical analysis, we believe that it is a valuable effort. With further research efforts using PCK Maps, we believe that the PCK Map approach will be refined and better serve various research purposes in the field of PCK that will produce useful implications for practice. The refined approach will then afford teacher educators to better support teachers' learning to teach since learning to teach involves not only developing individual knowledge components but also understanding how to employ them in an integrated fashion to apply to complex and contextualized problems of practice (Abell, 2008).

Overall, the findings of this study converge on the point that the synthesis of the components into PCK is not a straightforward process related primarily to simple possession of those components. Rather, the constructions of PCK are largely influenced by the interaction of different components (Hashweh, 2005). It is not always the case that an increase in one component simultaneously enhances integrity and functioning of the whole PCK. Lack of coherence among the components can be problematic in developing PCK. Also, increased knowledge in a single component may not be sufficient to stimulate change in practice. In this regard, to help teachers develop PCK, emphasis should be placed not only on the amount of knowledge in individual constituent components but also on the growth in the connectedness and complexity of PCK as a whole.

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