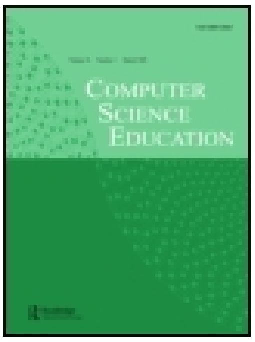

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ARTICLE

Pedagogical content knowledge in computing education: a review of the research literature

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ABSTRACT

This review synthesizes literature on computing pedagogical content knowledge (PCK). Shulman introduced PCK in the 1980s to describe the amalgam of knowledge teachers draw upon in their work and use of the construct is increasing in the computing education community. From a systematic search of the literature, I identified 19 articles drawn from 9 countries for review and summarize how computing PCK is conceptualized and investigated in the data set. Five conceptualizations of computing PCK were present: (a) two models of computing PCK components, (b) one model of PCK development and (c) two models focused on the metaphoric and problem-solving nature of computing. The most common research lines addressed were the nature and development of individual PCK. Mostly qualitative methods created by authors were employed. A focus on discipline-specific approaches for future computing PCK research is recommended.

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Introduction

> They can take all the code they have written in class so far, drop it in Processing, and it will run because Processing really is Java. It just makes graphics easier … I think that is an effective way to teach recursion … I think it is [more fun] to sort red squares on the checkerboard than it is to sort just numbers on the console. I am very visual. I find that more interesting, so I think some of the kids will find that more interesting. (Hubbard, 2017)

In this quote, Mr. Edwards (pseudonym) describes why he introduced the topic of recursion using Processing in a course focused on object-oriented programming and Java. He felt his students would better understand and enjoy recursion if they applied the concept to a visual task. Mr. Edwards' pedagogical decision involved more than subject matter knowledge, he also drew on his knowledge of student motivation and his past experiences teaching recursion. In other words, Mr. Edwards drew upon multiple types of knowledge whose combination is unique to teaching.

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Research on such specialized teaching knowledge that extends beyond general pedagogy and an understanding of content dates back to the 1980s (Matthews, 2013). For example, the Cognitively Guided Instruction group examined knowledge of teaching addition and subtraction by assessing elementary teachers' ability to distinguish problem types, judge the relative difficulty of problems and anticipate student problem-solving strategies (Carpenter, Fennema, Peterson, & Carey, 1988). Shulman (1986) introduced pedagogical content knowledge (PCK) as a theoretical construct to describe this specialized teaching knowledge which he defined as knowledge of

> the most regularly taught topics in one's subject area, the most useful forms of representation of those ideas, the most powerful analogies, illustrations, examples, explanations, and demonstrations … [it] also includes an understanding of what makes the learning of specific topics easy or difficulty. (p. 9)

PCK has been extremely influential in the study of teacher learning particularly in mathematics (Depaepe, Verschaffel, & Kelchtermans, 2013) and science (Schneider & Plasman, 2011).

Since its inception, researchers have revised Shulman's model and proposed additional constituent knowledge areas including types of learning tasks and their cognitive demands, assessment, educational ends, curricula and media, and context (Depaepe et al., 2013; Park & Oliver, 2008). Some of the more popular PCK conceptualizations derived from Shulman's work are Teacher Education and Development Study: Learning to Teach Mathematics (TEDS-M), Mathematical Knowledge for Teaching (MKT), Professional Competence of Teachers Cognitively Activating (COACTIV) and Knowledge for Algebra Teaching (KAT) (Blömeke & Delaney, 2012; Matthews, 2013). While researchers have progressed in specifying PCK components, the varied conceptualizations of PCK have not converged on a clear definition of the construct and many subdomains of PCK are difficult to distinguish (Hashweh, 2005; Matthews, 2013).

Scholars employ a variety of methods to study PCK. For example, many researchers have investigated teaching knowledge with CoRe (content representation) (Loughran, Mulhall, & Berry, 2004). CoRe consists of eight interview items designed to elicit and document the declarative PCK of a group of teachers. The group first selects a big idea in a domain and then discusses open-ended prompts that probe for factors influencing how the big idea is taught. CoRe is used in conjunction with PaP-eR (i.e. pedagogical and professional-experience repertoires), which provides a narrative description of how a teacher enacts PCK in practice. Another commonly used instrument is the survey of Technology Pedagogical Content Knowledge (TPACK; Schmidt et al., 2009). TPACK extends Shulman's model of PCK to include a focus on teaching with technology. Respondents completing the 46-item, Likert-type TPACK survey self-assess their knowledge of technology, content, pedagogy and the intersections of these three areas. Scholars have offered guidance on selecting methods to study PCK and its development. For example, Baxter and Lederman (1999) recommended researchers employ multiple methods and ask teachers to articulate their PCK given the often tacit and multifarious nature of teacher knowledge. Goldsmith, Doeer and Lewis (2014) cautioned against the overreliance on self-reported data of instructional practices because there may be differences between the ways teachers and researchers perceive practices. Despite such guidance, an unclear definition of PCK complicates the selection of study methods (Park, Suh, & Seo, 2017).

Due to its muddled definition and related issues of creating and selecting appropriate research methods, some researchers question the utility of PCK in its current form (e.g. Settlage, 2013). Other scholars suggest that consensus on the characteristics of PCK can help a research community advance both its knowledge base of specialized teaching knowledge and the research designs used to study the construct (e.g. Abell, 2008). However, Shulman recently reminded the field that "there will be plural perspectives on PCK, more than one legitimate, exciting, and fruitful way of thinking about PCK" (Shulman, 2015, p. 12). He further emphasized that his conception of PCK, which emerged as a response to views of teaching knowledge prevalent in the 1970s and 1980s that largely ignored content, excluded many factors that current PCK researchers should address such as noncognitive attributes of teaching, pedagogical action, sociocultural contexts and student outcomes. Thus, if we allow for a pluralistic view toward PCK and expand its purview to account for a more holistic picture of teaching, then the construct can remain productive for understanding that special knowledge teachers draw upon in their work.

In a review of the computing education research landscape covering 1976–2000, Holmboe, McIver and George (2001) noted limited references to pedagogical theory and a preponderance of papers that provided reflections from computer scientists on their teaching. Within computing teacher preparation work, a limited focus on PCK has also been noted at both the preservice level (Armoni, 2011) and in-service level (Menekse, 2015). To strengthen the identity of computing education research as its own discipline, Holmboe et al. (2001) encouraged a common goal of supporting the development of PCK through more empirical research that draws on existing educational theories and borrows methods from other disciplines. While research on computing PCK is relatively new, this review serves to summarize how computing PCK is conceptualized and investigated within computing education research. I do not aim to synthesize the entire knowledge base of computing PCK. Rather, by focusing on how the construct is defined and studied in computing education research, the findings of this review can inform future empirical efforts focused on computing teaching and teacher learning.

Methods

Computing education research is a relatively young field influenced by the methods, research designs and philosophical worldviews of various fields like psychology, computing and education (Fincher & Petre, 2004). These communities vary in expectations for the dissemination of scholarly work and the value placed on different forms of dissemination (Joy, Sinclair, Sun, Sitthiworachart, & López-González, 2008). Accounting for this variety, I conducted a review of the literature by searching for both academic journals and conference proceedings in the following databases that index scholarly work from the education, computing and engineering communities: Education Research Complete, Psychology & Behavioral Sciences Collection, SocINDEX with Full Text, American Psychological Association PsycARTICLES, Education Resources Information Center (ERIC), ACM Digital Library and IEEE Xplore Digital Library.

Publication titles and abstracts were searched for the terms (a) *computer science teachers* or (b) *computer science* in conjunction with *professional development, pedagogical content knowledge* or *teacher preparation*. The initial search returned 314 results. Only papers written in English, or providing a summary in English, and focused on secondary teachers of computing were included. It should be noted that in the global movement to expand computing to more students, there are two main approaches: teaching computing as its own subject and integrating computing into other disciplines (Ragonis, 2009). In this review, I focus explicitly on the former. Many courses under the latter approach focus on computational thinking, a concept popularized by computer scientist Jeanette Wing that describe ways of “solving problems, designing systems, and understanding human behavior, by drawing on the concepts fundamental to computer science” (2006, p. 33). Several articles are available for readers interested in teaching knowledge related to computational thinking (e.g. Angeli et al., 2016; Weintrop et al., 2016; Yadav, Mayfield, Zhou, Hambrusch, & Korb, 2014).

Additional exclusion criteria were used to identify articles for this review. Opinion pieces were excluded. Conference papers were excluded if they described a poster or provided only an abstract. Papers focused on professional development and teacher beliefs and identity were excluded because Armoni (2011) and Menekse (2015) addressed these topics in earlier reviews. Papers addressing other knowledge areas used in teaching (e.g. content knowledge) without including a focus on specialized teaching knowledge were excluded. Three conference papers could not be accessed. Inclusion and exclusion criteria winnowed the list to 12 papers.

Searching through online databases will only reveal a percentage of articles relevant to a literature review, so other techniques such as reference branching are recommended to help researchers identify additional articles of interest (Randolph, 2009). I identified seven additional articles to include in this review through reference branching. Unlike all other articles in the data set, one paper identified through reference branching drew on teaching experiences at the tertiary level. Another paper was identified in the reference list of an article written by Shulman (1987). In total, 19 papers are included in this review. Some papers in the final data set describe the same line of work and, where appropriate, are summarized together.

The findings are presented in two sections. First, a summary of the five computing PCK conceptualizations found in the data set is offered. In the second section, I focus on methods used to study computing PCK and summarize factors (i.e. country of work, PCK dimensions, computing topics, participants, materials) influencing the choice of methods in PCK studies. All articles in the data set are included in this second section. In the concluding section of the review, I provide a summary of the major research lines and main findings from these papers and offer suggestions for future scholarship on computing PCK.

Findings

Conceptualizations of computing PCK

Teaching subcultures vary by discipline (Grossman & Stodolsky, 1995) and PCK is influenced by content knowledge (Goldsmith et al., 2014). So, while PCK models were developed from scholarship in other disciplines, there may be aspects of computing PCK that differ from other domains and require revisions to these existing models or the creation of new models. Eight articles in the data set offered five conceptualizations of PCK to address topics and challenges unique to the discipline of computing. The conceptualizations vary in their focus on holistic models of PCK, PCK development or examples of PCK specific to computing. Most articles were published recently between 2004 and 2015; one article was published in 1987. The conceptualizations draw on educational materials, participants and experiences from multiple countries including Germany, Israel, the Netherlands, the United Kingdom and the United States. In the following paragraphs, I provide a description of each conceptualization and its creation process.

Two sets of articles produced holistic models of computing PCK. Baxter (1987), a student of Shulman, conducted a case study of two experienced secondary teachers in the United States who taught programming courses in BASIC to explore their CK and PCK related to programming, loops and sorting. Each teacher participated in three interviews, two structured tasks and 4 weeks of classroom observations spread across 8 weeks. Through a cross-case analysis of this data, Baxter arrived at four conclusions about PCK. First, CK and PCK may be more integrated in expert teachers than in beginning teachers, with expert educators using teaching as an organizer of their content knowledge. Second, cognitive styles (i.e. preferred, routine ways of acquiring information) influence how teachers attend to, store and use their CK. Third, teachers' educational goals relate to their instructional practices and may stem from their views of the purpose of education or their subject matter understanding.

Lastly, through interactions with students, teachers observe student conceptions and receive feedback on how well their instructional methods support student learning, which in turn supports their own PCK development. Baxter's resulting model of PCK included five areas of knowledge: alternative representations, student preconceptions, relationships among domains, substantive structure of the discipline (i.e. concepts and theories of a subject) and syntactic structure of discipline (i.e. ways new knowledge is acquired in a field such as inquiry processes in biology).

More recently, Kompetenzen für das Unterrichten in der Informatik (KUI) produced four articles providing a general computing PCK model (Bender et al., 2015; Hubwieser et al., 2013a; Hubwieser, Magenheim, Mühling, & Ruf, 2013b; Margaritis et al., 2015). KUI was a multi-institutional research initiative funded by the German government between 2012 and 2015 with the goal of creating a competency model that could inform computing teacher training. This group first created a system to categorize teacher education curricula by reviewing PCK literature, teacher education standards, prior conceptualizations of computing PCK, computing education research publications, educational research in other disciplines and textbooks on computing pedagogy. The resultant categorical system consisted of three dimensions: (a) *fields of pedagogical operation* which described 3 phases of the teaching process that occur before, during and after lessons; (b) a*spects of teaching and learning* which described 15 categories related to other pedagogical components (e.g. subject and curriculum, teaching methods) and (c) *noncognitive competencies* which described 17 categories related to social and communication skills, motivation and self-regulation, and beliefs and attitudes. Thirteen experienced secondary computing teachers and 10 computing teacher educators participated in the empirical validation of the model. Participants were presented with teaching scenarios related to each phase of the teaching process and asked how they would respond to the situation. The resultant model contained three components: PCK, teachers' beliefs and motivational orientations. The PCK component was divided into two dimensions: content and process. Content dimensions included subject and curriculum-related issues, teaching methods and uses of media, learner-related issues, teacher related issues and issues of the educational system. Process dimensions included the fields of pedagogical operation. In addition to PCK, the KUI model highlighted the role of beliefs and motivation in teaching. The KUI model also included concrete descriptions of teaching competencies related to each framework category.

Lapidot (2005) used an inductive approach to arrive at a model of computing PCK development. Lapidot conducted a study of 15 secondary teachers and preservice teachers in Israel across 4 years using observations, interviews and document analysis. Five preservice teachers were analyzed more deeply during their participation in a practicum course. One in-service teacher was followed across a year of teaching functional programming. Another in-service teacher was followed across 3 years while teaching the first lesson on recursion. Lapidot used the results of this analysis to create a four-stage content reasoning model to explain how computing secondary teachers learn, based on Shulman's (1987) model of pedagogical reasoning. In the first stage, *comprehension*, teachers focus on learning the content they need to teach. In the second stage, *transformation*, teachers focus on ways of turning their content knowledge into instructional examples. During this stage, teachers may identify gaps in their content knowledge and return to the first stage. In the third stage, *teaching*, teachers focus on students and their understanding while they teach. In the final stage, *reflection*, teachers try to improve their practice by analyzing their own teaching and their students' understanding. Lapidot also found that teacher learning was influenced by cognitive, social and affective factors.

The last two papers provide examples of PCK specific to computing. Woollard (2005) argued that since metaphor is embedded in the design of computational tools (e.g. icons); it plays an important role in the teaching of computing through pedagogic metaphor. Pedagogic metaphors, such as secret notes to represent the idea of encryption, were defined as "a literally untrue description of a concept or body of knowledge … a description, in the form of words, actions, images or diagrams, of an element of teaching" (Woollard, 2005, p. 197). Six data sets were analyzed to identify and categorize pedagogic metaphors: 19 teacher interviews, 32 journal articles related to PCK, 18 teaching resources, 3 exams, 20 computing topics considered difficult to teach and 20 computer metaphors Woollard identified in earlier work. Using a grounded theory approach, Woollard categorized the metaphoric approaches along two axes. The first axis categorized metaphors as either kinesthetic (i.e. concrete, based on devices and actions) or theoretical (i.e. conceptual, not linked to physical artifacts or activities). Along the second axis, metaphors were categorized as either traditional (i.e. common in the computing community) or novel (i.e. created by individuals in response to their teaching environments). An example of a kinesthetic, traditional metaphor of recursion is Russian dolls. An example of a theoretical, novel metaphor of recursion is a spiral turning. Woollard described the resultant PCK taxonomy as a tool to identify various nonliteral explanations of computing concepts that can be used to address conceptual difficulties, isolated topics, learner misconceptions and less interesting subject matter.

Koppelman (2008) drew upon research literature and personal teaching experiences when focusing on ways to conceptualize computing PCK. He first asserted that computing is about solving problems, and students acquire problem-solving skills through active learning opportunities in the form of exercises. He also argued that computing PCK is intricately tied to using exercises as a teaching tool. Koppelman devoted some attention to the question of how PCK about problem-solving exercises can be shared. He offered pedagogical cases as a tool for disseminating PCK and provided two examples related to UML design. The first case presented an exercise to support students struggling with the use of association classes. The second case presented an exercise to help students struggling to understand when to use a description class. In addition to providing exercises, the cases also discussed student misconceptions and common errors related to the sample exercise and how the exercise can address student difficulties.

How is computing PCK investigated?

PCK is a challenging construct to recognize and elicit. For example, ideas about teaching and learning are often unconscious and expressing these ideas may be an unfamiliar activity for teachers (Baxter & Lederman, 1999; Loughran, Gunstone, Berry, Milroy, & Mulhall, 2000). Also, educational challenges related to preparing teachers vary across locales and determine which PCK factors are important to study (Shulman, 2015). So, scholars use a variety of methods to investigate PCK for a variety of reasons, which are sometimes related to the contexts within which they work. In this section, I first identify the methods used to study computing PCK and the research questions addressed with these methods. Then I categorize each article along four dimensions that might influence choice of methods and research questions (Depaepe et al., 2013): country where work was conducted, dimension of PCK, computing topics and participants and materials.

Some articles in the data set represent the same line of work. The first set of articles represent work by KUI (i.e. Bender et al., 2015; Hubwieser et al., 2013a, 2013b; Margaritis et al., 2015; Ohrndorf & Schubert, 2013, 2014). The second set of articles represents work by Saeli and colleagues (i.e. Saeli, Perrenet, Jochems, & Zwaneveld, 2012b, 2012a, 2010). Unless otherwise stated, the articles related to each line of work will be summarized together as one article, providing 12 articles for analysis.

Research methods and questions

Scholars used a variety of methods (see Table 1) to understand computing PCK including interviews, tasks, document analysis, classroom observations, meeting observations and questionnaires. Most articles employed multiple methods; only three articles employed a single method (i.e. Buchholz, Saeli, & Schulte, 2013; Giannakos et al., 2014; Schulte, 2008). One article (i.e. Koppelman, 2008) can be considered more of an experience report and did not include methods.

While the majority of researchers developed their own instruments, a few scholars made use of existing instruments. Two projects used Loughran, Mulhall and Berry's (2004) CoRe tool. In some studies, scholars administered

Table 1. Methods used in review articles.

	Interviews	Classroom observation	Meeting observation	Task	Questionnaire	Document analysis
Baxter (1987)	×	×		×		
Buchholz et al. (2013)				×		
Giannakos et al. (2014)					×	
Griffin et al. (2016)	×	×				
Koppelman (2008)	N/A	N/A	N/A	N/A	N/A	N/A
Lapidot (2005)	×	×				×
Liberman et al. (2012)	×	×		×		
Ragonis and Hazzan (2009)	×			×	×	
Schulte (2008)			×			
Woollard (2005)	×					×
KUI ARTICLES						
Bender et al. (2015)	×					
Hubwieser, Berges, et al. (2013)						×
Hubwieser, Magenheim, et al. (2013)	×					×
Margaritis et al. (2015)	×					×
Ohrndorf & Schubert (2013)	N/A	N/A	N/A	N/A	N/A	N/A
Ohrndorf & Schubert (2014)				×		
SAELI ARTICLES						
Saeli et al. (2012a)						×
Saeli et al. (2012b)				×		
Saeli et al. (2010)			×	×		

the CoRe as intended with groups of teachers (Saeli et al., 2010), while others converted it into a questionnaire completed by both individuals and groups (Buchholz et al., 2013) or used it as a framework to analyze textbooks (Saeli et al., 2012a). Giannakos et al. (2014) used a subset of Schmidt et al.'s (2009) TPACK assessment to survey computing teachers in Greece about their teaching knowledge and needs.

Depaepe et al. (2013) identified six research lines in their review of mathematics PCK research: the nature of PCK (i.e. portrayals of PCK, refinement of the construct), the relationship between PCK and content knowledge, the relationship between PCK and student outcomes, the relationship between PCK and personal factors, the relationship between PCK and instructional practice and the development of PCK. The research questions authors identified in their articles were categorized along these six research lines and along a seventh research line (i.e. assessment of PCK) that also appeared in the data set (see Table 2). The most common research lines addressed were the nature of PCK and the development of PCK. A smaller number of articles addressed PCK assessment, instructional practice, personal factors or content knowledge. Just over half the papers focused on a single research line. A focus on personal factors and CK always appeared in conjunction with another research line. No papers in the data set focused on the relationship between PCK and student outcomes.

Table 2. Summary of PCK dimensions and research lines addressed in review articles.

		PCK Research Lines Addressed						PCK Dimensions Addressed		
Article	Country	Nature	CK	Personal factors	Instructional practice	Development	Assessment	Enacted	Individual	Collective
Baxter (1987)	U.S.		×		×			×	×	
Buchholz et al. (2013)	Germany					×			×	
Giannakos et al. (2014)	Greece	×		×					×	
Griffin et al. (2016)	U.S.				×			×		
Koppelman (2008)	Netherlands	×							×	
Lapidot (2005)	Israel		×		×	×		×	×	
Liberman et al. (2012)	Israel					×		×	×	
Ragonis and Hazzan (2009)	Israel					×			×	
Schulte (2008)	Germany					×				×
Woollard (2005)	U.K.	×							×	×
KUI ARTICLES										
Bender et al. (2015)	Germany	×							×	
Hubwieser, Berges, et al. (2013)	Germany	×								×
Hubwieser, Magenheim, et al. (2013)	Germany	×							×	×
Margaritis et al. (2015)	Germany	×		×						×
Ohrndorf & Schubert (2013)	Germany						×		×	
Ohrndorf & Schubert (2014)	Germany						×		×	
Schubert (2014)										
SAELI ARTICLES										
Saeli et al. (2012a)	Netherlands	×					×			×
Saeli et al. (2012b)	Netherlands	×	×				×		×	
Saeli et al. (2010)	Belgium, Italy, Lithuania, Netherlands	×								×

Countries

Teaching is a cultural process and differs across countries (Blömeke & Paine, 2008). Furthermore, computing education varies widely by country because some regions of the world are just beginning to offer rigorous computing education, while other regions have offered computing courses for a much longer time (Hubwieser et al., 2015). Along this spectrum of implementation stages are varying pathways into the computing teaching profession, multiple curricula and different types of professional learning opportunities; all factors related to PCK and its development.

Nine countries were represented in the data set: Belgium, Germany, Greece, Israel, Italy, Lithuania, the Netherlands, the United Kingdom and the United States (see Table 2). Countries including work from multiple scholars were Germany, Israel, the Netherlands and the United States. Only the work of Saeli and colleagues spanned multiple countries. Given that countries vary in their stage of computing education and in contexts that influence methodological approaches, differences in how computing PCK is studied in different countries are expected. In the following sections, I highlight when such differences appeared in the data set.

PCK dimensions

PCK, like other types of knowledge, can take different forms such as factual knowledge, conceptual knowledge, procedural knowledge or metacognitive knowledge (Anderson & Krathwohl, 2001). Each of these forms of knowledge requires different types of methods for assessment (Shavelson, Ruiz-Primo, & Wiley, 2005). Forms of PCK can be viewed as existing at different dimensions. Park and Oliver (2008) described two of these dimensions as knowledge-in-action used during the enactment of teaching (i.e. enacted knowledge) and knowledge-on-action used to prepare for teaching lessons. Loughran et al. (2004) offer a third dimension by distinguishing individual knowledge-on-action from collective knowledge-on-action because "PCK resides in the body of science teachers as a whole while still carrying important individual diversity and idiosyncratic specialized teaching and learning practices" (2004, p. 374).

All three dimensions of PCK were present in the data set. All but one article or article set included a focus on individual knowledge-on-action. This dimension of PCK was addressed in all nine countries included in the data set. A third of the article sets focused on collective knowledge-on-action, gathered from work conducted in Belgium, Germany, Italy, Lithuania, the Netherlands and the United Kingdom. A third of the articles focused on enacted knowledge, gathered from work conducted in Israel and the United States. While most articles focused on one PCK dimension, three articles looked at both individual knowledge-on-action and enacted knowledge. Another three articles looked at both individual and collective knowledge-on-action. No articles considered all three dimensions of PCK or collective knowledge-on-action in conjunction with enacted knowledge.

Computing topics

There is some consensus amongst researchers in other disciplines that PCK should be considered at the topic level, because teachers develop and make use of their PCK through experiences teaching specific topics (Abell, 2008; Hashweh, 2013; Park et al., 2017). For this reason, I identify the computing topics considered in the data set. Twenty-six computing topics were described in the data set. The majority of these topics stem from the work of Saeli and colleagues, who gave participants the choice of selecting which topics to discuss in their studies. Topics unique to their studies were arrays, control structures, data structure, decomposition, direct and indirect referencing, formal language grammar and syntax, functions, generalization, input and output, logical thinking, parameters, problem-solving skills, procedures, reusability, thinking in modules, user interface and variables. Excluding topics unique to the Saeli and colleagues papers, six computing topics were covered in the data set: algorithms, bubble sort, metaphor, programming, recursion and UML. Programming was addressed in seven articles. In addition to exploring specific computing topics, Griffin, Pirmann and Gray (2016) looked at a curriculum used in the United States (i.e. Computer Sciences Principles) and KUI focused broadly on the discipline of computing.

Participants and materials

PCK develops with experience and appears to progress through stages (Schneider & Plasman, 2011). For this reason, I also identify which levels of teaching experience are considered in the articles. Teacher participants across the articles covered all levels of experience including preservice teachers (Buchholz et al., 2013; Lapidot, 2005; Ohrndorf & Schubert, 2014; Ragonis & Hazzan, 2009; Schulte, 2008), in-service teachers (Baxter, 1987; Bender et al., 2015; Giannakos et al., 2014; Griffin et al., 2016; Hubwieser et al., 2013b; Koppelman, 2008; Lapidot, 2005; Liberman, Kolikant, & Beeri, 2012; Margaritis et al., 2015; Ragonis & Hazzan, 2009; Saeli et al., 2012b, 2010; Woollard, 2005) and teacher educators (Bender et al., 2015). Most research focused on in-service teachers included experienced teachers familiar with the computing concepts studied. However, one article (i.e. Liberman et al., 2012) looked at *regressed experts* or experienced computing teachers learning a programming paradigm new to them. Most articles included 30 or fewer participants. An exception to this pattern, Giannakos et al. (2014) distributed the TPACK survey to 1,127 secondary teachers in Greece, reaching 65% of the secondary computing teacher population. Also, Saeli et al. (2012b) distributed an adaptation of the CoRe instrument to 69 secondary teachers in the Netherlands.

Four articles also analyzed existing curricula to understand computing PCK (Hubwieser et al., 2013a, 2013b; Koppelman, 2008; Margaritis et al., 2015; Saeli et al., 2012a; Woollard, 2005). Work with in-service teachers was present in all countries represented in the data set. However, work with preservice teachers was limited to Germany and Israel. The research conducted in Germany crossed all three levels of teaching experience and analysis of curricula. Research from other countries focused on only one or two levels of teaching experience.

Conclusion

The purpose of this article was to synthesize the literature base on computing PCK research to identify how the construct has been conceptualized and investigated within the computing education community. Regarding conceptualizations of computing PCK, the data set contained five models. Three of these models (i.e. Baxter, KUI and Lapidot) describe computing PCK or its development at a broad level, sharing similarities with PCK models created in other disciplinary communities. For example, the five components of Baxter's model are contained within Park and Oliver's (2008) compendium of PCK conceptualizations. The KUI model shares many similarities with the 2012 Consensus Model of PCK (Gess-Newsome, 2015), which describes teacher knowledge and skill as drawing on multiple knowledge bases and influenced by teachers' orientations and beliefs. Lapidot's four-stage content reasoning model contains parallels to the science teacher learning progressions presented by Schneider and Plasman (2011). Such models offer the computing education community frameworks that highlight the factors and processes we should attend to when investigating PCK.

Two of the models (i.e. Woollard, Koppelman) provide examples of collective PCK, or a synthesis of teaching knowledge gathered from multiple sources specific to the discipline of computing. Woollard (2005) demonstrated how the metaphoric nature of computing can inform the categorization of pedagogic metaphors used to explain concepts to learners. Similarly, Koppelman (2008) considered the problem-based nature of computing when proposing a format for portraying computing PCK as pedagogical cases centered around a computing problem specific to a particular topic. Such models offer not only portraits of computing PCK but also tools for understanding teaching knowledge of specific computing topics.

All articles in the data set were examined to identify the methods used to investigate computing PCK and to understand factors that influence the choice of these methods. Many articles included a small number of participants, employed qualitative approaches created by the authors and focused on mostly introductory level topics. Most research efforts explored the PCK dimension of individual knowledge-on-action, with a smaller number of papers focusing on enacted or collective PCK. These studies provided findings on the relationship between content knowledge and computing PCK, the development of PCK in computing teachers and factors that influence how computing teachers gain specialized teaching knowledge.

What have we learned about computing PCK from these five conceptualizations and various methods? One area of findings relates to CK. Scholars suggest that PCK and CK are intertwined and less distinct in experienced teachers (Baxter, 1987), confidence in CK does not guarantee confidence in the related PCK (Giannakos et al., 2014), lacking CK can influence assessment of PCK (Ohrndorf & Schubert, 2013, 2014), the format of CK assessment items might elicit different outcomes from teachers (Saeli et al., 2012b), and textbooks tend to be low on providing PCK and the specific textbooks used by teachers may not influence their CK (Saeli et al., 2012b, 2012a). Through comparisons with experienced teachers, both Baxter (1987) and Griffin et al. (2016) provided evidence of how individuals vary in the organization of their CK and the enactment of their PCK.

Several scholars provided insight into the development of PCK. Through work with preservice teachers, we saw that PCK develops slowly in stages through the act of teaching, and in some stages, there is a greater focus on one's own acting as a teacher (as opposed to, for example, student learning) (Buchholz et al., 2013; Lapidot, 2005). Scholars also demonstrated how certain tools like tutoring and models of programming understanding can support PCK development in preservice teachers (Ragonis & Hazzan, 2009; Schulte, 2008). Lastly, we learned that even experienced computing teachers go through developmental stages when teaching topics new to them, showing both novice-like and expert-like behaviors (Liberman et al., 2012).

A final group of papers called attention to noncognitive factors influencing PCK. Lapidot (2005), Baxter (1987) and the KUI papers highlight that various personal and contextual factors influence how teachers learn, what teachers can learn and the ways teachers implement their knowledge in practice. Namely, they remind us that PCK does not exist or operate in isolation by calling our attention to the influence of an individual's beliefs and motivations.

While computing education research may be considered a young field relative to other disciplines, this review demonstrates that researchers are building an empirically validated knowledge base of computing PCK. One promising direction to further the field's understanding of computing PCK is to focus on aspects of PCK unique to the discipline. Future PCK research could examine teaching in computer labs, which are an important component of computing learning environments (Hazzan, Lapidot, & Ragonis, 2015). For example, Liberman et al.'s (2012) case study of an experienced teacher learning a new programming paradigm revealed differences in enacted PCK when looking at her teaching in the classroom setting compared to the lab setting. While teaching in the lab, she demonstrated growth in CK and less use of ineffective teaching practices. Also, drawing on the wealth of research related to student understanding of computing could guide the development of methods attuned to unique features of computing PCK. For example, Schulte (2008) drew upon research on novice programmers to create a lesson planning tool for preservice teachers. Due to novices' difficulty understanding program execution, Schulte's lesson plan model included four levels of program execution teachers should attend to when deciding how to present a program to their students. More research efforts focused on the unique disciplinary aspects of teaching and learning computing could expand our understanding of how to better support teachers in acquiring the knowledge and skills needed to become effective computing educators.

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