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Identifying pathways of teachers' PCK development

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ABSTRACT

This paper describes a method of analysing teacher growth in the context of science education. It focuses on the identification of pathways in the development of secondary school teachers' pedagogical content knowledge (PCK) by the use of the interconnected model of teachers' professional growth (IMTPG).The teachers (n = 12) participated in a one-year action research project focused on their individual concerns related to teaching science. The use of the IMTPG revealed that teachers use different pathways of learning to develop different aspects of their PCK. For each PCK component, three distinct pathways could be identified, two of which clearly were associated with professional growth. When examining these two pathways in detail, it was found that (1) teachers learned about new instructional strategies and assessment methods mostly through literature reviews and discussions with peers and (2) teachers who analyzed and reflected on student learning as it happened in their classrooms developed understandings that helped them to select and apply instructional strategies to further promote student learning. Both the analytical method as well as the identification of the different developmental pathways help to better understand teacher development in the context of classroom practices.

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Pathways of growth; action research; pedagogical content knowledge; professional development; science education

1. Introduction

> My 6th grade students have a difficult time understanding science concepts on an abstract level. Heredity for example is a hard concept for most students and no matter what I do, it does not get the results …

This quote is from the journal of a teacher who was searching for innovative ways to teach genetics. This teacher did not seek to increase her content knowledge on genetics per se, but wanted to expand her knowledge on instructional strategies so she could teach heredity to her 6th-grade students in such a way that they could understand this concept - in other words, she needed to develop her *pedagogical* content knowledge (PCK). Central to the notion of PCK is the idea that instruction can only be effective if it is attuned to the ways in which students learn specific content (Van Driel & Berry, 2010). Therefore, PCK has been

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defined as 'the only knowledge used in classroom instruction that helps students understand specific concepts' (Gess-Newsome, 1999, p. 12). Research on the development of PCK has demonstrated that teaching experience and subject-matter knowledge are important, however, contextual and personal factors also shape PCK development (Van Driel & Berry, 2010). To date, we know little about how teachers construct and develop PCK in the context of teaching practice, and how this development can be effectively supported (Kind, 2009). Therefore, the aim of this study was to identify specific pathways of change in teachers' PCK and to understand how the design features of an action research program impacted upon these changes. Understanding the process of PCK development in a professional development program is relevant and not necessarily unique to the domain of science teaching.

2. Literature review

2.1. Pedagogical content knowledge

Shulman introduced the concept PCK as 'that special amalgam of content and pedagogy that is uniquely the province of teachers, their own special form of professional understanding' (Shulman, 1987, p. 8). At the heart of PCK lies what teachers know about (a) how their students learn specific subject matter, (b) the difficulties or misconceptions students may have regarding this subject matter, and (c) their knowledge of instructional strategies, such as representations (e.g. models, metaphors) and activities (e.g. explications, experiments) to teach this specific subject matter. These components are mutually related: 'The better teachers understand their students' learning difficulties with respect to a certain topic, and the more representations and activities they have at their disposal, the more effectively they can teach about this topic' (Van Driel, 2014, p. 849). Elaborating on Shulman's work, various scholars have proposed different definitions and conceptualizations of PCK (e.g. Gess-Newsome, 2015; Kind, 2009). In studies in the domain of science education research, the conceptualization of Magnusson, Borko, and Krajcik (1999) of PCK has become particularly influential, and various adaptations of it have been published (Friedrichsen, Van Driel, & Abell, 2011). Magnusson and colleagues conceived PCK as a separate and unique domain of knowledge, consisting of five components: (1) orientations towards teaching science; (2) knowledge of science curricula; (3) knowledge of instructional strategies; (4) knowledge of student understanding of science; and (5) knowledge of student assessment. The four latter components are thereby 'shaped' by teachers' overarching orientations towards teaching science, that is their knowledge and beliefs about the purposes and goals of teaching science. 'Knowledge of science curricula' refers to teachers' knowledge about the goals and objectives of science curricula (state and national). 'Knowledge of instructional strategies' covers knowledge of both subject-specific and topic-specific teaching strategies. 'Knowledge of student understanding of science' refers to teachers' knowledge about how students come to understand specific subject matter, about students' prior knowledge (including misconceptions), and what is difficult for students to learn. 'Knowledge of student assessment' refers to teachers' knowledge of methods for assessing student performance in a particular domain (Magnusson et al., 1999)

Both subject matter knowledge and teaching experience are vital to the development of PCK (Kind, 2009), hence pre-service or beginning teachers' PCK typically is very limited. However, the further development of teachers' PCK in the context of teaching practice appears to depend on various factors. Van Driel & Berry, (2010) has suggested that:

> The development of PCK is perhaps best viewed as a complex interplay between knowledge of subject matter, teaching and learning, and context, and the way in which teachers combine and use this knowledge to express their expertise. (Van Driel & Berry, 2010, p. 659)

The aim of the present study is to better understand the processes of change of PCK, in terms of its components as defined by Magnusson et al. The study focused on a group of in-service science teachers who participated in a professional development program that combined a summer institute with a one-year action research project.

2.2. Action research for PCK development

Studies on teachers' professional development have shown that high-quality professional development programs may benefit from the inclusion of a form of inquiry (Arons, 1989; Bybee, 1993; Little, 2001; Lotter, Harwood, & Bonner, 2006) that enables teachers to actively construct knowledge through practice and reflection (Guskey, 1986, 2002; Schön, 1983). Action research has proven to be an effective way for teachers to improve their teaching and acquire new knowledge from their own classrooms (Feldman, 2007; Ponte, Ax, Beijaard, & Wubbels, 2004; Trauth-Nare & Buck, 2011). Action research requires teachers to examine their own teaching in relation to their students' learning, for example, by collecting data from their students. By means of action research, teachers acknowledge their classroom problems, seek answers to these problems, and act responsibly to solve them. For instance, Ponte et al. (2004) studied the professional knowledge development through action research of in-service teachers over a period of two years. They found that, when left to themselves, teachers developed knowledge related to the domain of educational methods, techniques, and strategies, but rarely developed knowledge regarding other domains such as educational norms, values, objectives, or the relations between the phenomena in educational reality. However, when the teachers in Ponte et al.'s study received help from facilitators in their action research (i.e. to master the skills of action research), they developed knowledge in all domains.

Action research has been applied only a few times in the context of PCK development. In a study of pre-service science teachers, Justi & Van Driel (2005) incorporated the design of a lesson series in an action research project that was a part of a teacher education program. It was found that, in particular, reflective activities (such as writing reports and sharing experiences in collective meetings) stimulated the development of both subject matter knowledge and PCK of the participants. However, the role of facilitators was not part of that study, even though this role seems to be important (e.g. Elliott et al., 2009; Ponte et al., 2004). In the present study, teachers were supported by academic staff to facilitate the process of action research and data were collected concerning the interaction between these facilitators and the teachers.

In order to study the teachers, PCK development within this context, we searched for a model of teacher learning with which we could describe (a) cognitive and behavioral aspects of the individual teachers' PCK development, (b) aspects of external input that influences this learning (e.g. facilitators), (c) different ways of teachers' learning, and (d) the role of student understanding with respect to subject matter. The Interconnected Model of Teacher Professional Growth (IMTPG) matched these criteria and was therefore used as an analytical tool to study the processes of PCK development that occurred in the context of teachers' action research projects.

2.3. Teachers' professional growth

A major question in teacher change literature relates to the issue of whether and how changes in knowledge, beliefs, and attitudes relate to changes in teacher practice (Bolhuis, 2006; Richardson & Placier, 2001). For a long time, it has been widely assumed that when teachers change their knowledge, beliefs, and attitudes on, for example, new instructional methods, their teaching practice will improve and accordingly result in better student outcomes. Since the middle of the 1980s, however, ideas about teacher change have been more focused on learning through reflection on one's own practice (Guskey,1986; Korthagen, Kessels, Koster, Lagerwerf, & Wubbels, 2001). Guskey (1986, 2002), for example, pointed out that teachers learn every time a lesson is taught, a curriculum designed, an assessment administered, and so on. Contrasting the accepted discourse at that time, he proposed a model of teacher change, where a professional development program could cause changes in a teachers' practice, which in turn could lead to changes in students' learning, and therefore could result in changes in teachers' knowledge, beliefs, and attitudes. The important facilitating process Guskey showed in his work is reflection. In later studies, researchers, including Guskey, found that teacher change covers a complex system of processes in which teachers are engaged in active and meaningful learning (Borko, 2004; Clarke & Hollingsworth, 2002; Desimone, Porter, Garet, Yoon, & Birman, 2002; Guskey, 2002). Borko (2004) proposed a model in which the PD program, the teachers, the facilitators, and the context in which the professional development occurs are key elements in a professional development system. Borko suggests that the relations between these elements have been investigated in various studies. These studies focused on explaining factors found in each element, but were not explicit about how exactly the elements are related, thus leaving the nature of actual teacher growth processes vague (see also Desimone, 2009). The present paper addresses just this matter of relationships between different elements of the action research program and processes of PCK development, looking through the lens of change pathways drawing on the IIMTPG.

In 2002, Clarke and Hollingsworth introduced the IMTPG to study changes in teachers' knowledge as a result of active and meaningful learning:

> Teacher growth becomes a process of construction of a variety of knowledge types (content knowledge, pedagogical knowledge, and PCK) by individual teachers in response to their participation in the experiences provided by the professional development program and through their participation in the classroom. (Clarke & Hollingsworth, 2002, p. 955)

Clarke and Hollingsworth argued that teacher professional growth can best be understood in terms of reciprocal relationships between four different domains which encompass teachers' professional world: (1) the Personal Domain, which contains teachers' knowledge, beliefs, and attitudes; (2) the External Domain, which contains external sources of information or stimuli; (3) the Domain of Practice which involves professional experimentation; and (4) the Domain of Consequence, which contains salient outcomes related to classroom practice (see Figure 1).

Using this model, Clarke and Hollingsworth (2002) show that when learning happens in the teaching practice, often change in one of the domains is 'translated' into a change in another domain through mediating processes of enactment or reflection. 'Enactment' is defined as something the teacher does as a result of what 'the teacher knows, believes or has experienced' (Clarke & Hollingsworth, 2002). This is the case, for example, when

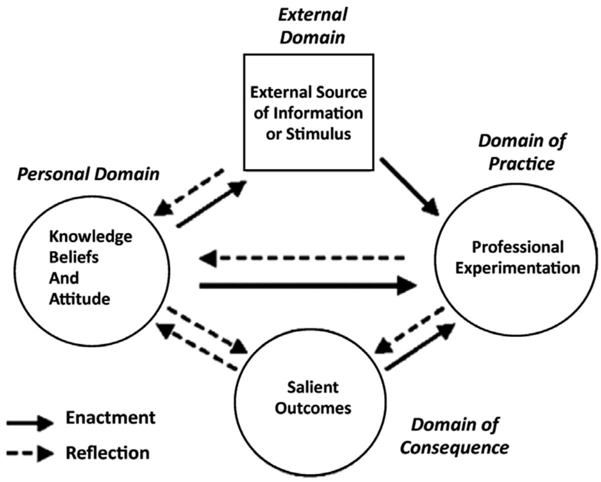

Figure 1. Clarke and Hollingsworth's (2002) IMTPG model.

a science teacher uses a certain analogy to explain the atom model, because s/he believes that it is a hard concept for students to understand. The term 'reflection' refers to 'a set of mental activities to construct or reconstruct experiences, problems, knowledge or insights' (Zwart, Wubbels, Bergen, & Bolhuis, 2007, p. 169). For example, when a science teacher realized that the analogy to explain the atom model enabled the students to visualize the model so that they understood the differences between the protons and the electrons. Clarke and Hollingsworth (2002) suggest that pathways for change appear through mediating processes of enactment and reflection. These pathways can result in either a 'change sequence' or a 'growth network.' Change sequences occur when a change in one domain leads to a change in another, supported by enactive or reflective links; a growth network is a more complex and ongoing change in more than one domain. In this paper, the focus is on change patterns, meaning translations of change in one domain into changes in other domains related to teachers' PCK development. Additional attention is given to the ways in which specific features of the action research program, located in the External Domain and the Domain of Practice, influence these patterns of change.

3. Context of the study

The study presented in this paper was conducted with middle and high school science teachers in the state of Illinois, USA, in the context of a one-year professional development program called the Mathematics and Science Partnership (MSP) program, which aimed at increasing teachers' professional knowledge, including but not exclusively, PCK. In this program teachers were encouraged to use action research to improve specific aspects of their classroom performance. The MSP program started with a two-week summer institute in which teachers were introduced to action research. In the first week, the teachers attended presentations from university staff on various science and mathematics topics, and best teaching practices related to these topics. Next, they selected a topic from their curriculum that they wanted to transform or improve the teaching of, and started to work on an action research plan in connection to this topic. In the second week of the summer institute, the teachers continued working on their plan, doing literature searches in order to deepen their understanding of the topic they had chosen, particularly on the teaching and learning of this topic. The teachers were asked to reflect upon their prior experiences teaching this topic, and what they thought about their students learning concerning this topic. On this basis, and their study of the research literature, they were asked to provide reasons why they might consider using different instruction methods in their projects. In this way, their PCK of the topic was challenged. The teachers developed research questions and identified appropriate methods of data collection. After creating lesson plans, they conducted their action research program in the following school year. During that year they had four meetings with the university staff, who acted as facilitators. The university staff facilitated the teachers' research processes and helped the teachers to answer questions regarding the content of their research. The facilitators made sure that teachers were on the right track and that they had a clear understanding of their action research project. Moreover, teachers consulted colleagues as critical friends who supported the participants to reflect on the progress and the outcomes of their action research project (Ponte et al., 2004). During the year, the teachers also kept an electronic journal to reflect on their projects. At the end of the program, all participants submitted an action research report.

4. Method

4.1. Research question

The following research question was central to the present study: *What might be possible pathways that lead to changes in science teachers' PCK in a professional development program?* To answer the research question, we formulated the following specific sub-questions (Agee, 2009):

(1) What pathways of change can be identified among the participants of a professional development program using the IMTPG model?
(2) How can the identified pathways be related to the development of science teachers' PCK?
(3) In what ways do specific characteristics of the professional development program contribute to development in the teachers' PCK?

4.2. Design

Given our aim to understand the process of changes of teachers' PCK in terms of pathways, and how the features of the professional development program contribute to these pathways, a qualitative design was chosen (Miles, Huberman, & Saldana, 2014). This design incorporated the use of data sources that would allow an in-depth look at teachers' change processes related to specific aspects of their professional expertise (i.e. PCK components). To answer the research questions, that is, to capture a variety of pathways, the study involved a limited number of participants with a range of backgrounds, contexts, and teaching experience.

4.3. Participants

Twelve in-service science teachers from middle and high schools in the state of Illinois, USA, volunteered to participate in this study (see Table 1). The criteria for participation were completion of their action research project, willingness to submit an action research report, and willingness to be interviewed as a follow-up on their action research project. To be part of the research, each participant was asked to sign consent forms to agree to participating in this research at the start of the MSP program. All participants that included test scores of their students in their action research reports obtained a consent form signed by the parents. During the PD program, a one-on-one interview was conducted at a convenient time and place for the participant. Each participant was informed that only fictitious names would be used in reports about the study, thus guaranteeing their anonymity.

The participants' schools were located in small rural communities. All participating teachers were present at the two-week summer institute, and the four follow-up sessions during the next school year. The teachers submitted an action research report which included lesson plans and did an interview with the first author.

4.4. Data collection

In order to understand the complex pathways of change for each PCK component, three data sources were used: the teachers' action research reports, their electronic reflective journals, and a semi-structured interview, which was conducted at the end of the project.

4.4.1. The action research report

At the start of the summer program, the participants received an electronic outline of an action research report. During the MSP program, the teachers worked on their action research reports while they documented their findings in this format. As the program continued, the teachers were able to build upon this document and make revisions. At the end of the year, it was this document that they submitted as the action research report; it also included an overview of their lesson plans and of products made by students that were collected during the year.

Table 1. Demographics of the teachers participating in the study.

Teacher	Name (fictitious)	Years of experience	Topic	Course	Grade level
1	Betsy	12	Deserts	Earth science	8th
2	Josh	7	Atomic theory	Chemistry	5th
3	Carlene	8	Rocks and minerals	Earth science	8th
4	Dana	17	The human body	Biology	4th
5	Diane	22	Cell structure	Biology	7th/8th
6	Donna	21	Volcanoes	Earth science	7th
7	Matt	28	Photosynthesis and respiration	Biology	7th
8	Norma	3	Cell structure	Biology	7th
9	Rhonda	26	Bats	Biology	7th
10	Shania	21	Cell structure	Biology	6th
11	Stephanie	10	The human body systems	Biology	7th
12	Trisha	2	Earthquakes	Earth science	4th

4.4.2. The electronic journal

All teachers kept a personal electronic journal in which they reflected on their personal progress. At some points during the MSP program, time was allotted for the teachers to write their experiences in this journal. They were asked to reflect on the presentations by the university staff and the workshop activities during the summer course, as well as on their findings in the classroom, their action research progress, and how they felt about the action research project. At the end of the year, the teachers submitted this journal as part of the data collection process.

4.4.3. The interview

After the teachers submitted their action research report and journal, the first author conducted interviews with the volunteering participants. During the interview, the teachers were asked about their action research project. Whenever more detailed information was needed on certain topics concerning the development of PCK, more probing questions were asked. For example, when a teacher wrote in her action research project about *the use of models to study the atom theory,* specific questions were asked about how the teacher learned about this method, how the method was used, and what her personal experience was of using that method to teach a specific science subject.

4.5. Adaptations to the IMTPG model

We adapted the IMPG model to the specific needs of our study. In the Personal Domain of the IMTPG, we included the four PCK components described in Magnusson et al. (1999). Furthermore, we created three sub-domains in the External Domain. We subdivided the External Domain into three sub-domains: university staff, peers within the action research program, and other external sources of information. In accordance with the study by Zwart et al. (2007), we divided the Domain of Practice into two sub-domains: preparing and teaching. In the professional development program, the teachers prepared an action research plan for their classrooms. This preparation was different from the general meaning of 'preparation' in the Domain of Practice, which means the preparation of lessons for classroom teaching. Furthermore, in order to study how a change in one domain triggers a change in another domain, we used, as customary in this model, the mediating processes of 'enactment' and 'reflection.' For our study, we used the criteria as adapted by Justi and Van Driel (2006) (see Table 2).

Sometimes, a change in one domain triggered changes in two different domains. In this case, we made an adaptation by using two arrows (equally numbered) to indicate parallel mediating processes (see Figure 2). For example, we found situations in which a change in a teacher's knowledge (Personal Domain) led to changes in his or her lesson plan (Domain of Practice), and at the same time, caused an adjustment of his or her action research plan (located in the External Domain). In such a case, two processes occurred simultaneously, and these were given the same number (see two arrows 1 in Figure 2).

4.6. Data analysis

Data analysis was conducted in the following steps:

Table 2. Criteria used in this study to establish relations in the IMTPG (adapted from Justi and Van Driel (2006)).

Relation	Mediating process	Criterion
From PD to ED	Enactment	When a specific aspect of the teacher's initial cognition or belief influenced what s/he did or said during the learning activities in which s/he took part
From ED to PD	Reflection	When something that happened during the learning activities modified the teacher's initial cognitions or beliefs
From ED to DP	Enactment	When something that happened during the learning activities influenced something that occurred in teaching practice
From PD to DP	Enactment	When a specific aspect of the teacher's cognitions or beliefs influenced something that occurred in teaching practice
From DP to PD	Reflection	When something that the teacher did in his/her teaching practice modified his/her cognitions or beliefs (without reflection on classroom outcomes first)
From DP to DC	Reflection	When the teacher noticed and reflected on something that s/he or his/her students did in teaching practice that caused specific outcomes (such as student learning, teacher control, student motivation, and student development)
From DC to DP	Enactment	When a specific outcome made the teacher state how s/he would modify the associated teaching practice in the future When a specific outcome made the teacher change his/her practice at that moment (reflection-in-action)
From DC to PD	Reflection	When the teacher reflected on a specific outcome, thus changing a specific aspect of his/her previous cognitions or beliefs When a teacher's evaluative reflection on the salient outcomes led to a change in cognition
From PD to DC	Reflection	When a specific aspect of the teacher's cognition helped him/her in reflecting on/analyzing a specific outcome of his/her teaching practice

Note. PD – Personal Domain, ED – External Domain, DP – Domain of Practice, DC – Domain of Consequence.

(1) All interviews were transcribed verbatim.

(2) All data were examined and selected for indications of teacher change. To record the changes, we used the following statements:

   (a) Changes in cognition included statements such as *I have learned that, I know how to, I understood why, etc.*

   (b) Changes in attitude or beliefs included statements such as *I feel that now I can, I believe now that, I am confident in, I think now I can, etc.*

   (c) Changes in perceived or intentional behavior included statements such as *Now I am doing, I used to do … but now I am doing …, I tend to do more …, I am doing things differently now, etc.*

(3) We categorized the selected statements indicating change to one of the PCK components suggested by Magnusson et al. (1999).

Example 1: *I found that I could use portfolios to assess experiments in photosynthesis* indicates teacher change in the use of an alternative student assessment tool. This statement was categorized as the PCK component *knowledge of students' assessment*.

Example 2: the statement: *Instead of explaining, I could use models to explain the atom theory* indicates change in using a different type of instruction. This was linked to the PCK component *knowledge of instructional strategies.*

All the statements from the three different sources were triangulated to ensure reliability and were then linked to each PCK component.

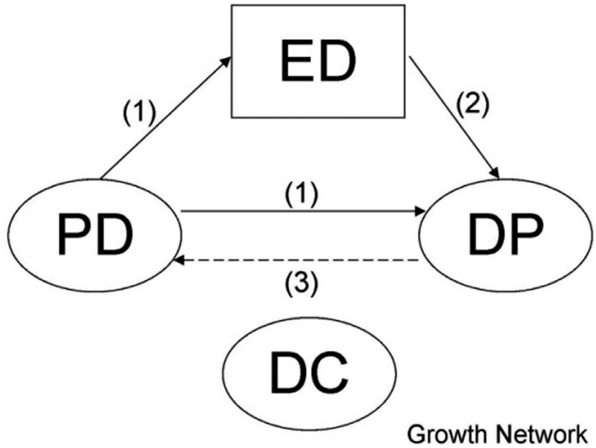

Figure 2. Simultaneous process in a growth network.

(4) Next, using the adapted criteria from Justi & Van Driel (2006) (Table 2), we examined these changes to determine if there were any relations between domains of the IMTPG. Then we determined in which domain the entry point occurred, and how this affected the other domains, especially in the Personal Domain, which includes the teachers' PCK (see Table 3). (10)

(5) We then constructed a pictorial representation (pictogram) for the development of each PCK component, showing relationships between the domains of the IMTPG (see an example of a pictogram in Table 3). We created one pictogram for each PCK component per teacher, which resulted in 48 pictograms.

(6) In accordance with the work of Zwart et al. (2007), we studied the 48 pictograms in order to identify particular pathways on the basis of the common entry points (start), the sequences of changes, and the end points. We investigated particularities of the pathways and discussed how one pathway differed from the others before agreeing on each pathway. After identifying the pathways, we categorized each pictogram by its particular pathway.

To strengthen the internal validity of the analysis, the selection and categorization of the patterns of change were conducted independently by the author and an independent researcher (Cohen, Manion, & Morrison, 2000), and the results obtained were compared. In only a few cases, there was a difference; in those cases, the discrepancy was discussed until agreement was reached.

5. Findings

For each component of PCK, we found different pathways of change. In this section, we discuss these pathways per PCK component by explaining how they were constructed and how they differed from each other. Where necessary or appropriate, the statements from the teachers' journals are used to explain the typical enactments and reflections associated with each of the pathways.

Table 3. Example of a pathway that indicates a change in a teacher's PCK component based on the teacher's data (based on instructional strategies of teacher Josh).

Sequence of processes	Relation between domains	Criteria (from Justi & Van Driel, 2006)
Josh reflects on the use of differentiated instructions in his lessons about atoms: *Differentiated instruction has been promoted through discussions with the university faculty as part of our professional development school partnership. I had been tentative about implementing differentiated instruction because of the commitment of the variety and quantity of materials, the difficulty of accurately assessing student performance, as well as being able to have reliable objective data to reflect on to determine if differentiated instruction would fit my current teaching style* (*from AR*)	External Domain to Personal Domain (arrow 1)	When something that happened during the learning activities modified the teacher's initial cognitions, behavior or beliefs
Josh decides to use differentiated instructions in the classroom: *Students working on differentiated projects were allowed to choose from differentiated laboratory activities and completed these activities within the same timeline as the standard. The goal was that all students would be able to explain the modern theory of the atom, read a periodic table and identify the symbol's name and determine the number of protons, neutrons, and electrons the element has, and identify the 4 basic chemical reactions* (*from AR*)	From External Domain to Domain of Practice (arrow 2)	When something that happened during the learning activities influenced something that occurred in the teacher's practice
Josh responds to this classroom strategy: *I find myself uncovering new features and gaining confidence in the use of differentiated instruction. I see increasing opportunities for classroom use. I still am not sure whether the commitment of managing 70 or more students would make this easier or just different from current methods. The idea of working in this setup is intriguing, but I will have to keep an open mind and wait and see what develops* (*from journal*).	From Domain of Practice to the Personal Domain (arrow 3)	When something that the teacher did in his/her teaching practice modified his/her cognitions or beliefs (without the teacher reflecting on classroom outcomes first)

5.1. *Knowledge of science curricula*

When investigating pathways related to the PCK component knowledge of science curricula, we identified three different pathways (see Figure 3). In this study, changes in the PCK component *knowledge of science curricula* were represented by two different types of pictograms (pictograms 2 and 3), whereas pictogram 1 did not indicate a change in the teachers' knowledge of the science curricula. In pictogram 1, the changes originated from the teachers' Personal Domains (entry point). These teachers used previous knowledge of goals and objectives in their action research planning (AR planning) and their lesson plans (see arrows 1), but did not show any reflection on their science curricula, thus showing no changes in their knowledge of science curricula.

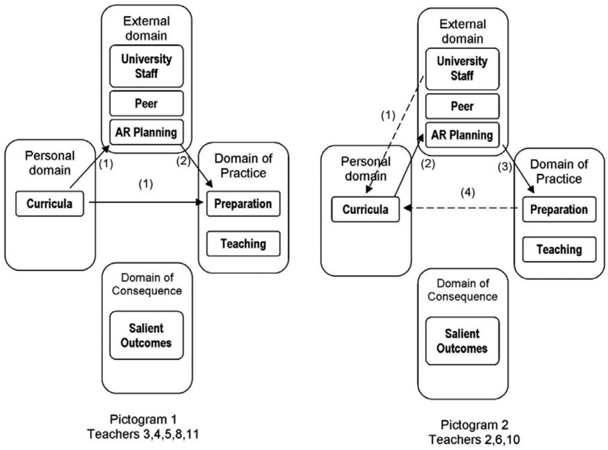

Figure 3. Pictorial representations of development of knowledge of science curricula.

In pictogram 2, the entry point was in the External Domain, where teachers consulted the university staff. An example of pictogram 2 from teacher 6: Donna, a 7th-grade science teacher, contacted the university staff.

> [The university staff] helped me a lot. She [university professor] did one presentation on molecular structure and bacteria and it was so good. I gained a lot of knowledge from presentations and mentoring. She [mentor] was very informative and anytime I needed [to know] something … She was my source of information. (arrow 1. source: teacher interview)

When conducting her action research, Donna reflected: *I do need to address the problem of heredity. I used the sites in my [classroom] project to integrate some ideas that address this issue* (arrows 2 and 3. source: teacher interview). After she had planned her lessons, Donna said: *I wanted them to learn and understand the structures of cells. And it was basically the beginning of microbiology, so I wanted them to get the basic framework to understand cellular structure* (arrow 4. source: teacher interview).

In the third pictogram, the teachers not only consulted the university staff, but also reviewed the literature to learn about their science curricula. For example, Matt (teacher 7), a 7th -grade high school teacher, used the presentations from the university staff and did a literature review on photosynthesis to improve his lessons: *I was forced to reflect on what I taught and began making changes* [*in the curriculum*] *based on the presentations from* [*the university staff*] (see arrow 1 in pictogram 3. source: reflective journal). After his literature review, Matt learned that

> … the microcomputer can now be used as a tool in the laboratory by students of all ages. The ability to connect a device (a probe) to the computer that can measure things in the real world (such as temperature, position, sound intensity, pH, light intensity and force) now allows students and teachers to acquire information about the world in a way that is new and exciting and can make a major contribution to the science conceptual development of the user. The ability of the microcomputer to transform these data into a real-time graph as the experiment progresses is a second critical contribution to conceptual development. (arrow 1. source: action research report)

Matt incorporated these findings in his action research plan (arrow 2) and prepared his lesson plan accordingly (arrow 3). At the end of the project, Matt reflected on his lesson plans:

This is a new area that I want to move into that offers great possibilities for student learning in regard to cellular respiration and photosynthesis (arrow 4. source: teacher interview).

5.2. Knowledge of instructional strategies

Data analyses for the PCK component *knowledge of instructional strategies* showed pictograms with similar entry points but with three different pathways leading to three distinctly different learning outcomes (see Figure 4). All entry points were in the External Domain, where teachers reviewed the literature. The participants used the literature extensively to search for appropriate instructional strategies for their lessons. Some teachers discussed their instructional strategies with their peers (pictograms 5 and 6), others did not (pictogram 4). After planning (arrow 2), preparing (arrow 3), and conducting their lessons, pictogram 4 teachers reflected on their lessons (arrow 4). An example from Dana (teacher 4):

> I used experiments while studying the human body because I wanted my students to have as many experiences as possible. I think that they do learn better by providing different evidence themselves, not just out of a book. (pictogram 4, arrow 4. source: teacher interview)

In pictogram 5, the teachers reflected on their classroom practice (arrow 6) and their classroom outcomes (arrow 7). An example of arrows 6 and 7: after Shania (teacher 10) taught her 6th-grade class on volcanoes, she explained that her students did not learn that much when they were taught in the traditional way. At the end of the program, she was convinced that her students did learn something:

> Now they remembered something … throughout their school life, an thing that has to do with cells will come back to them, and I think that alone makes a lot of difference. (pictogram 5, arrows 6 and 7. source: teacher interview)

Pictogram 6 illustrated the following: the teachers reflected on the input during the workshops from the university staff (arrow 1), they consulted their peers (arrow 2), they reflected on what they discussed with their peers (arrow 3), and prepared their action research accordingly (arrow 4). From their action research plan, they planned their teaching and reflected on this preparation (arrows 5 and 6). They enacted their resulting knowledge of instructional strategies in their lessons (arrow 7), and reflected on these lessons (arrow 8) and their outcomes (arrow9). These reflections led to further changes in their knowledge

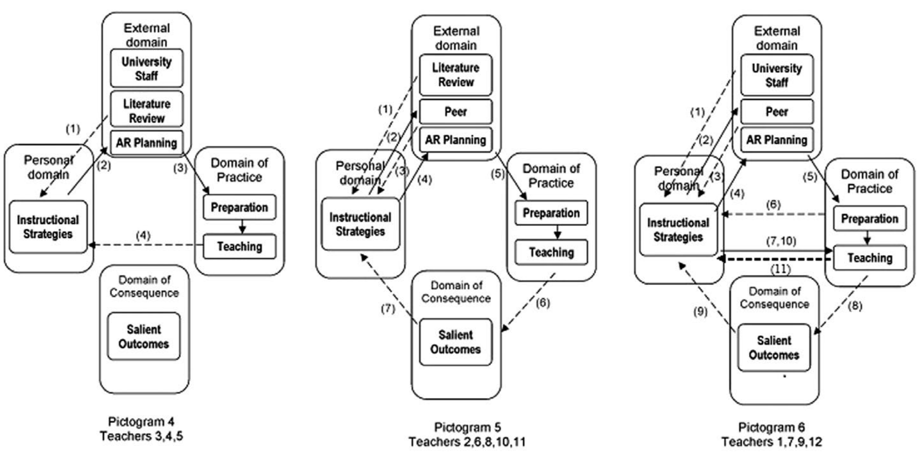

Figure 4. Pictorial representations of development of knowledge of instructional strategies.

of instructional strategies, which they enacted in order to change their classroom teaching (arrow 10), and again, they reflected upon their experiences in practice (arrow 11). Matt's (teacher 7) example of arrows 10 and 11:

> Through using them [micro-based computer labs], I was forced to reflect on how these types of labs work with seventh graders. I saw how they impacted the learning in my room as we reviewed video tapes of students doing microcomputer-based labs (arrow 9) … So the second time I did it [the micro-based computer labs] was actually better than the first. (arrow 11. source: teacher interview)

5.3. Knowledge of student understanding of science

Considering *knowledge of student understanding of science,* we found that science teachers used three different entry points from three different domains (see Figure 5): pictogram 7 shows that the science teachers started from the Personal Domain with some knowledge of how their students learned science best (pictogram 7, arrow 1). In pictogram 8, we see that the teachers were inspired by the university staff on how students learn science (pictogram 8, arrow 1). In pictogram 9, the entry point is in the Domain of Consequence, where teachers reflected on gaps in their students' knowledge left after previous classroom experiences (pictogram 9, arrow 1).

Pictograms 8 and 9 showed similarities, where teachers consulted university staff in their process of developing knowledge of student understanding. Here are two examples of university staff contributions: Josh (teacher 2) reflected on the presentations given by the university staff:

> I saw another way to teach the science content to students. This activity [integrated presentations] can be used at any grade level. It helped me to grow in my ways of teaching by showing me the ways the students learn and giving me their perspective. (pictogram 8, arrow 1. source: reflective journal)

Matt (teacher 7) said that

> a lot of new things were presented in either math or science. I found out a lot of things about how children learn: they learn better by doing and we picked up on the research that was done that we could use in our classroom. (pictogram 9, arrow 3. source: reflective journal)

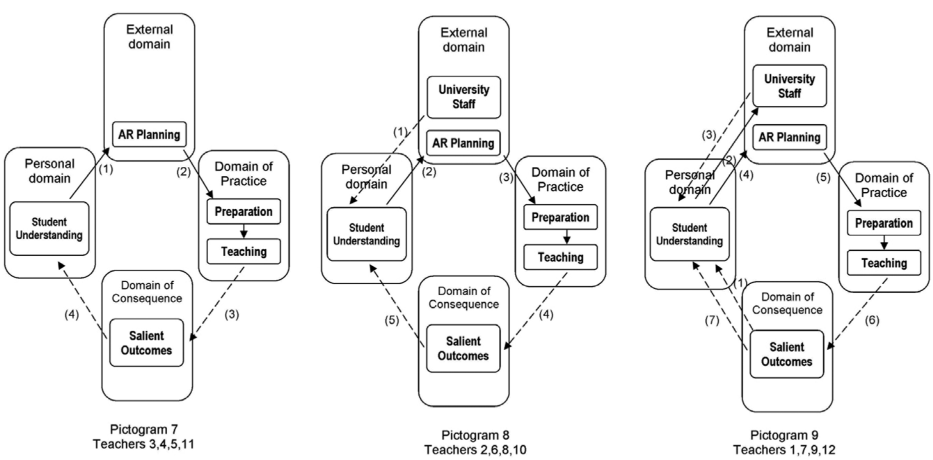

Figure 5. Pictorial representations of development of knowledge of student understanding of science.

In all situations related to knowledge of student understanding, we found that teachers used classroom outcomes to reflect on student learning. Example from Betsy (teacher 1):

> The part where the students taught themselves was a strong feature. I think they learned more about earthquakes when they were doing the teaching themselves. So they took ownership of their project and that is what turned it into a success. (pictogram 9, arrow 6. source: teacher interview)

5.4. Knowledge of student assessment of scientific literacy

In *knowledge of student assessment of scientific literacy,* the entry points were all in the External Domain, but in different sub-domains (see Figure 6). Pictogram 10 showed that the teachers started with peer discussions about what assessment methods were appropriate for their lessons. Pictogram 11 teachers received guidance on assessment methods from the university staff. They reflected on assessment methods but did not use classroom outcomes as part of these reflections. Donna (teacher 6) reflected: *after I do a lesson I often, as just a part of the evaluation, go through and reflect upon what worked* (pictogram 11, arrow 4, source: interview). In pictogram 12, the teachers first consulted the literature and then asked a colleague to discuss ideas. Pictogram 10 teachers did not reflect on their classroom practice. Pictogram 12 teachers used classroom outcomes to reflect on assessment methods. A final example from Matt (teacher 7):

> During the actual project at the time, when we were looking at respiration and photosynthesis, I was looking at the group interaction and what was happening to them (pictogram 12, arrow 6. source: teacher interview). It did make me see the kids doing certain things [performing certain skills] that I probably was not aware of before … I have also found that my students are much more capable of doing sophisticated work than I thought. (pictogram 12, arrow 7. source: teacher interview)

6. Discussion

The central question of our study was: *What might be possible pathways that lead to changes in science teachers' PCK in a professional development program?* We discuss the different pathways that we found in more detail in this section.

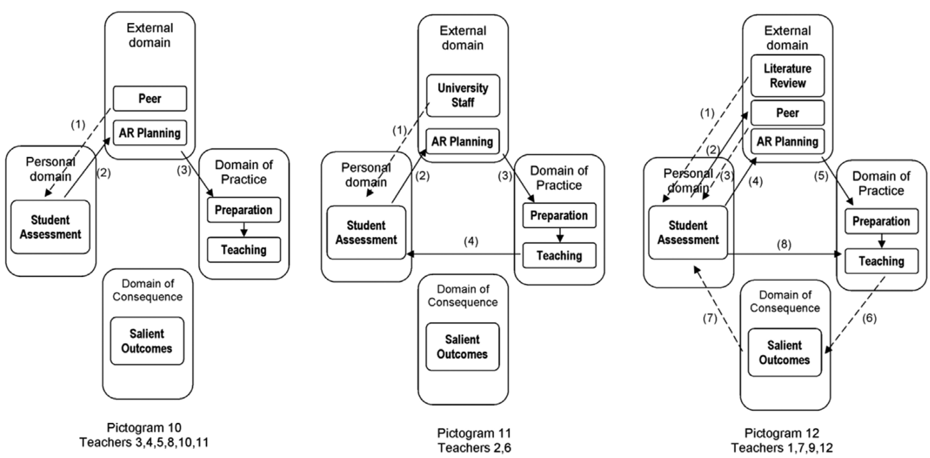

Figure 6. Pictorial representations of development of knowledge of student assessment of scientific literacy.

6.1. Different pathways related to PCK development

Although we found unique pathways for each individual teacher, we were able to categorize these pathways, based on similar entry points, similar IMTPG domains, and similar ending points. We want to discuss three distinct pathways that teachers could follow when participating in the MSP.

First, we encountered a pathway that did not lead to changes in the teachers' PCK. This pathway, illustrated in pictogram 1, indicated that five teachers did not change their knowledge about science curricula. Although, there were relationships between different domains, this pathway merely represented some 'change sequences' (Clarke & Hollingsworth, 2002, p. 958). These change sequences may have occurred, because these teachers already knew the science curriculum, or were not interested in learning about this topic and therefore did not show any development of their PCK.

Second, we found two other distinct pathways that did lead to changes in PCK: (1) pathways that included the Domain of Consequence (see pictograms 5, 6, 7, 8, 9, and 12) and (2) pathways without the Domain of Consequence (pathways in pictograms 2, 3, 4, 10, and 11). Clarke and Hollingsworth (2002, p. 958) used the term 'growth networks' when more than two relationships exist between different domains. They stated that 'growth networks' demonstrated professional growth and reflected ongoing and lasting changes. In our study, pathways *without* the DC reflected 'simple growth networks,' whereas pathways *including* the DC could be seen as more 'complex growth networks.' When closely examining those pathways showing a 'simple growth network,' we did find changes in the different domains; however, the teachers did not demonstrate whether they learned from reflecting on the results of their classroom actions. For example, Dana (teacher 4) reflected on her knowledge of instructional strategies after preparing lesson plans, but did not reflect on how her students perceived this new way of teaching (see pictogram 4). On the other hand, in the pathways with a 'complex growth network,' the teachers reflected on their students' learning (by explicitly considering the Domain of Consequence), and were able to specify what they learned from their students. For example, Matt (teacher 7) reflected on the teaching strategy used in his classroom, using video recordings to analyze the effects on his students, and was able to argue whether the instructional strategy was effective or not (see pictogram 6). These findings show that reflections on classroom outcomes were important for the PCK development of these in-service teachers.

We also conclude that there were two distinctly different groups of teachers in this study, based on their pathways to PCK development. One group (teachers 3, 4, and 5) showed similar pathways in pictograms 1, 4, 7, and 10, while the other group (teachers 1, 7, 9, and 12) showed the same pathways in pictograms 3, 6, 9, and 12. The pictograms of teachers 2, 6, 8, 10, and 11 had pathways with patterns different to these two groups. The pathways in their pictograms were too scattered to determine a clear pattern in their learning.

Interestingly, however, when comparing the two distinctive groups, we concluded that the second group of teachers was consistently reflecting on their actions and changes, while the first group showed fewer reflections in their pathways. In particular, the second group (i.e. teachers 1, 7, 9, and 12) had pathways including reflections from the Domain of Consequence, except for the PCK component *knowledge of the science curricula*. It appeared that following on their reflections on the Domain of Consequence, these teachers were able to enact from their Personal Domain in order to revise their classroom teaching (see pictograms 6 and 12). On the other hand, pathways found for the first group of teachers (i.e. teachers 3, 4, and 5) did not include this Domain of Consequence, except in the pictograms on *knowledge of student understanding* (pictogram 7). Focused and structured reflecting on students' learning thus seemed to be an important catalyst to PCK development.

6.2. Powerful elements in the professional development program

In the two distinct pathways that led to PCK development, an investigation of the different entry points led us to conclude that changes in the External Domain often induced major changes in the PCK found in the Personal Domain. In detail, 41 of the 48 entry points were located in the External Domain, where 14 of these entry points were linked to the university staff, 17 entry points were found when teachers used their literature review, and 10 were prompted by teachers participating in peer discussions. We noted that the university staff contributed most in helping participants define science curricula, and in constructing knowledge of student understanding. This is an interesting finding since the role of facilitators in enhancing teacher knowledge is important in professional development (Timperley, Wilson, Barrar, & Fung, 2007), but does not get the proper attention it deserves in studies on professional development (Hill, Beisiegel, & Jacob, 2013). The literature review and peer discussions were used extensively in the search for instructional strategies and assessment methods. It should also be noted that teachers valued the use of the educational and science literature reviews to change and experiment in their teaching. When teachers studied the literature, they were able to adapt their instructions more to current recommendations from this literature (pictograms 3, 4, 6, and 10). This tallies with the findings of other scholars (Fennema et al., 1996; Rhine, 1998). Rhine (1998) found that resources on educational research can be crucial for in-service teachers as a 'lifelong resource' for lesson planning. Although reading research publications is still seen as an informal experience in professional development (Ganser, 2000), we concluded that teachers may benefit from it. Teachers in this study used the literature to find information on science topics and to learn about effective ways to teach these topics. Then when they discussed their findings from the literature with peers, this helped them reflect on this newfound knowledge, providing a deeper understanding of their PCK (pictograms 6 and 12). Furthermore, many teachers conducted their literature reviews with an eye to problems or concerns that had arisen from previous classroom experiences. In general we found that teachers who conducted a literature review and participated in peer discussions acquired a better understanding of the use of instructional strategies and assessment methods, such as the use of micro-based computer labs to increase students' science skills, and the use of students' journals to assess their students' knowledge. In the planning of professional development programs, therefore, teachers' reading of educational research literature should be considered, since it creates opportunities to construct new knowledge.

6.3. Conclusions and implications

For researchers studying professional development programs, it is important to examine the content of the teachers' experiences, the processes that occur, and the contexts in which they occur (Fielding & Schalock, 1985; Ganser, 2000). It is also important to be able to monitor changes in teachers' long-term processes. The IMTPG is a model that serves to capture such changes, making it possible to describe the changes and uncover the processes for research purposes. In this study, the model was useful to show changes in teachers' PCK by way of their processes of enactment and reflection. Furthermore, this model has shown differences between teachers' PCK development processes, acknowledging that PCK is indeed personal and context bound. Our use of the model also illustrated that professional development is not a linear process, but rather a complex network of processes sometimes occurring simultaneously. We found evidence that the Domain of Consequence plays a crucial role in a teacher's PCK development. More attention should be paid to how this domain interacts with the other domains. Furthermore, when we adapted the IMTPG by refining the different domains, it became evident that specific factors in one domain triggered changes in other domains. For example, we found that the university staff in the external domain triggered teachers' knowledge of instructional strategies. This makes the model very useful as an analytical tool by which to investigate teachers' knowledge development. Analyzing data according to this model shows how changes in teachers' knowledge occur, why they occur, and sometimes under what circumstances they can occur. Clarke and Hollingsworth (2002) have argued that professional development programs should offer participants the opportunities to enact change in a variety of forms. In this study, action research was found to be a successful way to stimulate teachers to change their practice; therefore, action research could be incorporated in professional development programs. To focus teachers on analyzing and reflecting on student learning in their classrooms, action research needs to be embedded in a design that includes support, such as external sources (e.g. research literature) and facilitators (e.g. university staff and peers). In this way, action research is a powerful approach to enhance teachers' professional knowledge and adapting their practice based on their own increased understandings of student learning (cf. Lesson study; Xu & Pedder, 2014).

Disclosure statement

No potential conflict of interest was reported by the authors.

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