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Inquiry-Based Science Education Competencies of Primary School Teachers: A literature study and critical review of the American National Science Education Standards

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Inquiry-based science education is an important innovation. Researchers and teachers consider it to be stimulating for pupils' application of research skills, construction of meaning and acquiring scientific knowledge. However, there is ambiguity as to what competencies are required to teach inquiry-based science. Our purpose is to develop a profile of professional competence, required for effective inquiry-based science teaching in primary schools in the Netherlands. This article reviews literature and compares the outcomes to the American National Science Education Standards (NSES). In so doing, it seeks to answer the following research questions: What elements of competencies required by primary school teachers who teach inquiry-based science are mentioned, discussed and researched in recent literature? To what extent are the American NSES (introduced 15 years ago) consistent with elements of competencies found in recent literature? A comprehensive literature review was conducted using Educational Resources Information Centre and Google Scholar databases. Fifty-seven peer-reviewed scientific journal articles from 2004 to 2011 were found using keyword combinations. Analysis of these articles resulted in the identification and classification of 22 elements of competencies. This outcome was

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compared to the American NSES, revealing gaps in the standards with respect to a lack of focus on how teachers view science teaching and themselves as teachers. We also found that elements of competencies are connected and poor mastery of one may affect a teacher's mastery of another. Therefore, we propose that standards for the Netherlands should be presented in a non-linear, holistic, competence-based model.

Keywords: *Pedagogical content knowledge; Primary school; Teacher knowledge*

Introduction

Good-quality teachers, with up-to-date knowledge and skills, are the foundation of any system of formal science education. Systems to ensure the recruitment, retention and continuous professional development of such individuals must be a policy priority in Europe (Osborne & Dillon, 2008). Many stakeholders hold the expectation that the gap between labour market and education can be reduced through competence-based education. When the emphasis is on developing competencies, and not just acquiring a diploma, the accent of education needs to be on capabilities, not on qualifications (Biemans, Nieuwenhuis, Poell, Mulder, & Wesselink, 2004).

However, there is no nationally accepted science teaching competence standard in the Netherlands and now that several courses of teacher training colleges for primary education are (or will soon be) competence-based, such a standard is needed.

National science teaching standards have been used in the USA since 1996. Many researchers of inquiry-based science education both in the USA (see for example: Choy & Ramsey, 2009; Eick & Stewart, 2010; Park Rogers, 2009; Varma, Volkmann, & Hanuscin, 2009) and outside the USA (see for example Avraamidou & Zembal-Saul, 2010; Lin, Hong, & Cheng, 2009; Shymanski, Yore, & Anderson, 2004) have used these standards to define inquiry-based education and to study inquiry-based science teaching competencies. Considering that these standards are referred to in international journals, and that they are the product of an open, iterative process involving different groups of stakeholders, thus reflecting a broad consensus reached 15 years ago about the elements of science education, we decided to evaluate whether they can still be used as an example for the current European context. Specifically, we aimed to investigate whether additions or changes should be made to the standards based on research findings published in the period 2004–2011. American pupils of the age of 10 years score higher than average on international comparative research and higher than most Western European pupils (Gonsalez et al., 2009), which is not necessarily a result of the standards, but the standards might have had a positive effect on the quality of education and the pupils' results. The context in which science is taught: culture of education with its pluralistic views, culture of society as a whole and how science is represented are comparable between these continents, both being Western industrialised societies (Erikson, 2005). Both education systems recognise plurality, not a unitarian approach, which requires a generic model. Thus, the American standards and additions or changes based on current literature might be helpful in future for a better understanding of what is required in the Dutch context concerning inquiry-based science competencies of primary school teachers.

This article presents the findings of a literature study conducted to answer the questions:

What elements of competencies required by primary school teachers who teach inquiry-based science are mentioned, discussed and researched in recent literature? To what extent are the American NSES consistent with elements of competencies found in recent literature? This article reviews recent international scientific literature and the American NSES to compare the elements of teacher competencies that are considered to be required for teaching inquiry-based science. The aim is to provide a better understanding of what is required in the current Dutch context concerning inquiry-based science competencies of primary school teachers, resulting in a profile for primary school teachers existing of elements of professional competence.

The study was part 1 of 4 projects of a network of research on inquiry-based science teaching. Study 2 aims to validate the outcomes of this literature study for the context of the Netherlands, using a Delphi approach. Study 3 aims to report the design of an instrument to assess teachers on inquiry-based science teaching, and study 4 aims to find characteristics of effective professional development programmes aiming to improve inquiry-based science teaching.

The first section of this article considers and reviews literature on inquiry-based science education and on teacher competencies with respect to inquiry-based education; the second section presents the methodology, the third, major section reports on the results of the study; and the fourth, final section discusses the conclusions that can be drawn from this work and their implications for future research and future practice.

Theoretical Framework

Inquiry-Based Science Education

Inquiry-based science education is considered to be an important current trend in science education reform. Scientific inquiry generally refers to the diverse ways in which scientists study the natural world (Liang & Richardson, 2009, p. 51). More than a procedure or a method, it is a process of investigating how, why or what, and then making sense of the resultant findings (Bhattacharayya, Volk, & Lumpe, 2009). Based on standards developed by the American National Research Council (NRC, 1996, 2000), many researchers (Avraamidou & Zembal-Saul, 2010; Cuevas, Lee, Hart, & Deaktor, 2005; Howes, Lim, & Campos, 2009; Liang & Richardson, 2009; Lin et al., 2009; Park Rogers, 2009; Smolleck, Zembal-Saul, & Yoder, 2006; Varma et al., 2009) mention six essential features of classroom inquiry that apply across grade levels. Learners address scientifically oriented questions; plan and carry out investigations to gather evidence; give priority to evidence in responding to questions; formulate explanations for evidence; connect explanations to scientific knowledge; and communicate and justify explanations. Scientific inquiry includes investigating natural phenomena through experimentation and higher thinking. This refers to thinking that goes beyond mere recording of data or mechanically applying concepts. The focus of inquiry is on the creation, testing and revision of scientific models and explanations, to create new knowledge and scientific reasoning (Schwarz & Gwekwerere, 2007). NRC describes inquiry as 'a multifaceted activity that involves making observations; posing questions; examining books and other sources of information to see what is already known; planning investigations; reviewing what is already known in light of experimental evidence; using tools to gather, analyse and interpret data; proposing answers, explanations and predictions; and communicating results' (NRC, 1996, 2000, p. 23). Other definitions also encompass processes such as using investigative skills; actively seeking answers to questions about specific science concepts; and developing the ability to engage, explore, consolidate and assess information. Inquiry is not a linear process; rather, aspects of inquiry interact in complex ways (Cuevas et al., 2005). Classroom inquiry introduces pupils to the content of science as well as the process of investigation. It provides the logical framework that enables students to understand scientific innovations (Smolleck et al., 2006).

Inquiry learning 'refers to the activities of pupils in which they develop knowledge and understanding of scientific ideas, as well as an understanding of how scientists study the natural world' (Luera & Otto, 2005, p. 243). Inquiry teaching is defined as 'providing a classroom where learners can engage in scientific-oriented questions to formulate explanations based on evidence' (Luera & Otto, 2005, p. 243). The aim of inquiry-based science education is to help pupils develop scientific skills and a deep understanding of the subject matter and the nature of science. Encouraging pupils' questions and aiding them in learning to utilise evidence from the real world to address these questions are essential to inquiry-based education (Howes et al., 2009).

Inquiry-based education may include different degrees of inquiry learning depending on the learning environment. Science education researchers have developed an inquiry continuum that classifies classroom inquiry into different levels from structured inquiry to open inquiry. To determine whether a lesson activity can be categorised as full or partial inquiry, one must consider the amount of student and teacher involvement in each of the essential features of classroom inquiry (Smolleck et al., 2006; Varma et al., 2009). Leonard, Boakes, and Moore (2009) and Liang and Richardson (2009) refer to Windschitl (2003) who described several levels of science inquiry: (1) traditional laboratory confirmation experiences providing pupils with step-by-step procedures to verify known principles in structured inquiry; (2) structured inquiry in which the teacher presents a question, lab equipment and procedures for pupils to discover an unknown answer; (3) guided inquiry through which teachers allow pupils to investigate a prescribed problem using their own methods of gathering and analysing data and drawing conclusions; (4) student-directed inquiry, in which the teacher presents a topic and lets pupils develop their own questions and design their own investigations; (5) open inquiry through which pupils form their own questions and conduct independent investigations.

There is empirical and theoretical evidence to support the assumption that inquiry-based science is a starting point first for increasing the motivation of pupils to learn about science (Lin et al., 2009); second, for applying research skills (Cuevas et al., 2005) and third, for personal construction of meaning and deeper learning of content knowledge (Luera & Otto, 2005; Weld & Funk, 2005). School science courses are often seen as dull and unexciting by pupils (Bhattacharayya et al., 2009); and science as inquiry is considered to be an important part of the solution to that problem. Pupils are offered more hands-on activities, with the aim of making science dynamic and physical and allowing pupils to feel comfortable with the subject (Howes et al., 2009). Giving them more opportunities to carry out investigations does not guarantee their engagement in learning; however, if pupils are encouraged to plan their own learning activities, they are more likely to get involved in a task (Lin et al., 2009).

Inquiry-based science education complements the natural curiosity of pupils by encouraging them to ask questions, try things out and evaluate the outcomes (Howes et al., 2009). Pupils should know how to pursue their own questions about the world around them. This pursuit, however, does not happen naturally in the classroom, and pupils will need to be supported in their attempts to understand phenomena. When science is taught through the process of inquiry, pupils have the opportunity to pose questions and seek answers based on observation and exploration. Pupils can then use the evidence gathered throughout this process to answer their own questions that may arise. Inquiry allows pupils the opportunity to explore, yet simultaneously requires them to learn something about how science research is conducted.

Many educational theories presume that people learn best through direct personal experience and by connecting new information to what they already know (Bhattacharayya et al., 2009). Therefore, corresponding educational paradigms have shifted from reproducing knowledge towards asking scientifically oriented questions and searching for evidence in responding to questions (van Zee, Hammer, Bell, Roy, & Peter, 2005) and towards active, self-regulated learning aimed at (co-) construction of knowledge (Marble, 2007; Piaget, 1985). Thus, a rich learning environment, with a focus on inquiry-based learning, creates opportunities for pupils to identify their assumptions, use critical and logical thinking, internalise or transform new information, which then allows them to create and expand their individual cognitive structures (Smolleck et al., 2006). Through these activities, pupils develop their understanding of science by combining science knowledge with reasoning and thinking skills (Cuevas et al., 2005). Inquiry learning supports (long-term) conceptual understanding by supplementing the learning of scientific concepts and facts. Thus, inquiry-based science can lead to better performance in science classrooms. In summary, inquiry-based education might lead to a higher degree of scientific literacy, i.e. the knowledge and understanding of scientific concepts and processes required for personal decision-making, participation in civic and cultural affairs, and economic productivity. Scientific literacy includes specific types of abilities (NRC, 1996), and it expands and deepens over a lifetime, not just during the years in school. But, the attitudes and values established towards science in the early years will shape a person's development of scientific literacy as an adult. Primary school teachers influence pupils' attitude and values towards science and the development of pupils' scientific literacy (Shymanski et al., 2004).

Teacher Competencies with Respect to Inquiry-Based Education

As described, young pupils can develop a complex understanding of science when sufficient opportunities to learn are presented. Teachers' competencies influence pupils' learning (Vikström, 2008). In this research, we use the integrated, holistic and relational broad development approach on competencies. We view competence as the integrated performance-oriented capability of a person to reach specific achievements (Biemans et al., 2004, 2009; Mulder, 2001). Personal competencies comprise integrated performance-oriented capabilities, which consist of clusters of knowledge structures and also cognitive, interactive, effective and where necessary psychomotor capabilities, and attitudes and values, which are required for carrying out tasks, solving problems and, more generally, effectively functioning in a certain profession, organisation, position or role (Mulder, 2007). We acknowledge the cultural context and social practices involved in competent performance, reflecting how personal attributes are used to achieve outcomes in teaching within specific schools and within broader relationships with society. Thus, competencies have a strong relationship with organisational effectiveness (Mulder, Weigel, & Collins, 2006).

Competencies are assumed to be recognisable, assessable relevant for practice, and can be developed and learned (Mulder et al., 2006). Competence is not trained behaviour but thoughtful capabilities and a developmental process. A competence profile can be described as the overview of the essential elements of professional competence required for effective performance in a job (du Chatenier, Verstegen, Biemans, Mulder, & Omta, 2010). In practice, competence elements are integrated and cannot be separated because of the complexity and indeterminate nature of real-world situations but in theory individual competence elements can be distinguished.

Recent research has indicated that primary school teachers have difficulties in being effective inquiry-based science teachers. They tend to lack knowledge concerning how science inquiry works and, particularly, how to implement inquiry-based teaching in their classrooms (Lee, Hart, Cuevas, & Enders, 2004; McDonald & Butler Songer, 2008; van Zee et al., 2005). In addition, it depends on teachers' beliefs about the nature of science if scientific inquiry is implemented in the classroom (Eick & Stewart, 2010). If a teacher views science as a body of facts, no or little inquiry is offered to the children. In contrast, when a teacher considers science as inquiry and science knowledge as negotiated and constructed through inquiry, more inquiry experiences are presented in the classroom (Forbes & Davis, 2010). Park Rogers (2009) caution that even if inquiry-based science is implemented in the classroom, it does not automatically result in positive effects on pupils' learning. To engage pupils in inquiry and to teach science as exploration is not enough. Pupils need

	Working with pupils	Working with colleagues	Working with schools' professional environment	Working with him/herself, managing self (development)
Interpersonal	1	5	6	**7**
Pedagogical	2			
Expert in subject matter and teaching methods	**3**			
Organisational	4			

Figure 1. Dutch teacher competence matrix (Ministerie van Onderwijs, cultuur en wetenschappen, 2004)

explicit instruction on science as inquiry including how to create knowledge through arguments based on explorations and evidence (Park Rogers, 2009). Teacher competencies are essential to increase pupils' science literacy, consisting of meaningful understanding of subject matter knowledge (SMK) of scientific facts and concepts; improvement of their science skills (Bhattacharayya et al., 2009; Smolleck et al., 2006) and interest in science (Lee, Lewis, Adamson, Maerten-Rivera, & Secada, 2007; Shymanski et al., 2004).

The Dutch Parliament passed the 'Professions in Education Act' in 2004 (Ministerie van Onderwijs, cultuur en wetenschappen, 2004). The essence of the act is that educational personnel must not only be qualified but also competent. For this reason, sets of competencies and its requirements have been developed. The framework of competence requirements specifies four professional roles that teachers have: interpersonal, pedagogical, and organisational and the role of an expert in subject matter and teaching methods. The teacher fulfils these professional roles in relation to four groups of actors in education: working with students, colleagues, the school's professional network and himself/herself. The framework specifies competence requirements for each role and in relation to the four mentioned actors in education. However, the guidelines are broadly defined and there are no specific competence requirements formulated for science.

In this research, we aim at giving an overview of the essential elements of professional competence, required for effective inquiry-based science teaching in the classroom. Therefore, we searched for competence requirements for working as an expert in science subject matter and science learning methods with pupils and managing self (development) in this regard (see Figure 1).

Methods

In order to answer the research questions, the online sources Educational Resources Information Centre and Google Scholar were searched for relevant articles published in the period of 2004–March 2011. The various searches and corresponding literature analyses took place from January 2009 to March 2011. The whole search and selection procedure and the most important stages and decisions related to the procedure are described below.

First, to find definitions of inquiry-based primary science teaching, the keywords 'teach' and 'science' were combined with 'inquir'. A second search that combined 'teach', 'science', 'inquir' and 'competenc' was performed to find articles on primary teacher competencies in inquiry-based science education. Based on the definition of competence presented by Mulder (2007) and Mulder et al. (2006) we replaced 'competenc' with the synonym 'capabilit*', and 'knowledge', 'attitude*', and 'skill', since these are seen as clusters of underlying capabilities of competencies. The abstracts of the identified articles included the thesaurus descriptors 'scientific literacy', 'belief', 'PCK' (i.e. referring to pedagogical content knowledge (PCK)) and 'teaching methods', again as underlying capabilities of competencies. To obtain more relevant (peer-reviewed) articles of interest, those words were also used in the search for articles, replacing 'competenc'. 'Journal articles' as a type of source and 'elementary' or 'primary' as a level of education were used in all searches. To reduce the number of articles to a manageable set, while enhancing the chance of including the most important articles, only articles from leading journals found in the Journal Citation Report and the International Science Index of the Web of Science were used. These journals included the *International Journal of Science Education*, *International Journal of Science and Mathematics Education*, *Journal of Elementary Science Education*, *Journal of Research in Science Teaching*, *Journal of Science Teacher Education*, *Research in Science Education*, *Research in Science and Technological Education*, *Science and Education*, *Science Education*, *School Science and Mathematics*, *Teaching Science*, *Teaching Science and Technological Education*. The search with keywords identified 432 papers. After excluding those not published in the scientific journals mentioned above, this number was reduced to 186. We included both larger and small-scale studies, and selected papers that contained any competence expressions. A quick scan of the abstracts of the selected papers was conducted to exclude articles on subjects other than science competencies of primary school teachers. After excluding articles with an emphasis on mathematics; learners and their improvement; the learning environment or the characteristics of professional development programmes for teachers as well as those related to contexts other than primary schools, 126 articles remained. Finally, duplicates resulting from two or more searches were excluded, resulting in 57 papers. Those remaining were evaluated for their potential relevance to the topic. The full texts of the resulting articles were acquired from the Wageningen University and Research Centre Library. Articles not available were requested through the interlibrary service.

We looked for any mentioned, required or desirable element of competencies of primary school teachers who teach science. Based on the definition of competence presented by Mulder (2007) and Mulder et al. (2006), the 22 elements found in the articles were then categorised into three clusters of underlying capabilities: knowledge, attitude and skills. This was helpful, but we realised that the cluster 'knowledge' consisted of different types of knowledge and the cluster 'attitude' included very different aspects. We then minimised the cluster 'knowledge' to declarative knowledge. This includes knowledge about facts and concepts, and the knowledge of inquiry (isolated as well as applied and related) and resembles what Lee, Maerten-

Rivera, Buxton, Penfield, and Secada (2008) and Park Rogers (2009) also call SMK. Other types of knowledge, dealing with pedagogy and/or didactics were moved to the cluster 'skills'. In the literature, this category, together with other aspects, is referred to as 'PCK' (Akerson & Volrich, 2006; Avraamidou & Zembal-Saul, 2005, 2010; Park Rogers, 2009). We renamed this cluster 'science PCK', since this is a more accepted term in recent (science) education research and practice.

We subsequently looked through the articles for references to original sources of information on PCK, which led us to Shulman (1986a, 1987), Grossman (1990), Magnusson, Krajcik, and Borko (1999). Based on these articles, we then added two competence elements that we found in the articles, namely, 'attitude towards science teaching' and 'attitude towards science learners and learning' to the science PCK cluster. We kept aspects of attitude that do not belong to PCK (according to the definition of Magnusson et al., 1999) and those that do influence enacted practice ('attitude towards science', 'attitude towards self as a teacher' and 'teachers' attitudes towards their own professional development') separate in the cluster 'attitude'.

Results

In this section, the underlying capabilities for the competence 'to be an expert in science subject matter and science learning methods, working with pupils and managing self(development) in this regard' (see Figure 1), as mentioned and discussed in literature, are reported. The 22 elements that were found are categorised in three clusters of the competence underlying capabilities: SMK, attitude and PCK.

Cluster of Underlying Capabilities 1: Teachers' Science SMK

Teachers cannot teach what they do not understand. Teachers therefore need accurate and comprehensive mastery of science content in order to teach science successfully (Katz, Sadler, & Craig, 2005; Lee et al., 2004). Deep and complex understanding of science involves memorising and understanding factual information and concepts; understanding the relationships between those concepts and knowing when and how to apply them in context (Glen & Dotger, 2009; Lee et al., 2009; Leonard et al., 2009). Both pupils and teachers must be provided with multiple exposures to both definitional and contextual information about vocabulary in order to deeply learn it and use it in their reading, writing and speaking. Language as a labelling system is needed to allow pupils to further understand concepts. In classrooms studied by Glen and Dotger (2009) however, language as a labelling system was overused. Little attention was paid to language as an interpretive system, particularly the transition from interpretive language to the technical terms of science and the role interpretive language plays in debates and controversy used in scientists' claims (Glen & Dotger, 2009). By not using language as an interpretive system, teachers may carry on the image of science as easy fact finding.

An expert's knowledge is connected and organised around important concepts, while a novice's knowledge is often fragmented. A person with disconnected knowledge will find it more difficult to retrieve relevant information and transfer it to appropriate situations (Luera & Otto, 2005). Moreover, teachers possessing a high level of connected subject matter expertise are more likely to engage in conceptually rich, inquiry-based activities that facilitate student learning. They tend to focus on the core responsibility of teaching: their pupils' understanding of the subject matter (Dietz & Davis, 2009). Science consists of five subsystems: living systems or biology, physical systems, earth and space systems, technological and mathematical systems (Weld & Funk, 2005). Understanding the relation between concepts and knowing when and how to apply them allows teachers to flexibly use knowledge of one system, for example mathematics, to solve or explain problems in another science system, for example biology (Liang & Richardson, 2009). Teachers with weak science content knowledge are more likely to rely heavily on textbooks as the main source of content knowledge and for the preparation of their lessons. This is problematic, since science textbooks often do not address pupils' alternative, non-scientific conceptions and a teacher with weak science knowledge will be unable to clarify pupils' understanding (Lee et al., 2009; Luera & Otto, 2005). Moreover, the extent of teachers' knowledge is tied to their interest in and attitude towards science, for example in geosciences (Leonard et al., 2009) or physics (van Zee et al., 2005).

Research shows that teachers exhibit deficiencies in their science content knowledge (Leonard et al., 2009) and they have alternative conceptions (Isabelle & de Groot, 2008; Trundle, Atwood, & Christopher, 2007). It is important, but not sufficient, for teachers to understand scientific theories and facts well enough to explain phenomena scientifically (Lee et al., 2004). In addition, teachers need knowledge about science and research or investigation skills (Akerson & Volrich, 2006). Various lists of required science process skills and knowledge have been proposed. They generally differ in the way individual items are expressed rather than at a more fundamental level. Each in its own way includes observation; raising questions, hypothesising, predicting, planning and carrying out investigations using tools, interpretation of information obtained and communication of information (Katz et al., 2005; Lee et al., 2009; Park Rogers, 2009). Thus, teachers must be able to develop arguments and justify their ideas or solutions based on evidence (see Figure 2). Doing so, they might acquire SMK concerning facts and concepts and (the purpose of) scientific language (Avraamidou & Zembal-Saul, 2005, 2010; Glen & Dotger, 2009; Liang & Richardson, 2009; Luera & Otto, 2005; Park Rogers, 2009; Schwarz, 2009; Trundle, Atwood, & Christopher, 2007). On the other hand, deepening and connecting SMK of science facts and concepts influences the quality of research skills, such as posing questions (van Zee et al., 2005) and communicating and justifying results (Oliveira, 2009).

Cluster of Underlying Capabilities 2: PCK

Teaching inquiry-based science is challenging. Strong SMK is necessary but not sufficient for effective teaching. Teachers also need knowledge that blends subject matter and pedagogy (Avraamidou & Zembal-Saul, 2010; Davis, 2005). Therefore, the construct of PCK was introduced in 1986 by Shulman. He conceptualised it as the

Elements of teachers' science subject matter knowledge (SMK)

SMK 1: Knowledge of facts and concepts
SMK 1-1 Teachers' understanding of the meaning of isolated facts and concepts
SMK1-2 Teachers' understanding of the relation between facts and concepts of:
- *the same subject*
- *different subjects*

SMK 1-3 Teachers' understanding of when and how to apply facts and concepts
(related to living;, technological; physical; earth and space; and mathematical systems)

SMK 2: Teachers' understanding of inquiry skills
SMK 2-1 Teachers' understanding of the meaning of isolated research skills
SMK 2-2 Teachers' understanding of the relation between the research skills
SMK 2-3 Teachers' understanding of when and how to apply research skills
(Observe; pose questions and predictions; examine books and other resources of information to see what is already known; plan investigations; carry out investigations using tools to gather, analyse and interpret data; propose answers, explanations and predictions using data; communicate and justify results).

Figure 2. Elements of teachers' science SMK

knowledge of subject matter for teaching, including: 'the most powerful analogies, illustrations, examples, explanations, and demonstrations — in a word, the ways of representing and formulating the subject that make it comprehensible for others' (1986, p. 9). Shulmans' work led to a shift in understanding teachers' work such that research began to focus on understanding teaching from the teacher's perspective rather than focusing on evaluation and labelling of teachers and teaching behaviours. Many researchers responded to and further developed the notion of PCK (Grossman, 1990; Magnusson et al., 1999). Although PCK has attracted much attention, there is no universally accepted definition or conceptualisation. Abell (2008) encourages researchers to use PCK more explicitly and coherently, grounded on Shulmans' original ideas about teacher knowledge, to frame their studies. Along with the working definition of PCK, we identified five components of PCK for science teaching, mainly drawn from the work of Grossman (1990) and Magnusson et al. (1999): (1) orientations towards science teaching, (2) knowledge of curriculum, (3) knowledge of assessment, (4) knowledge of pupils' understanding of science and (5) knowledge of instructional strategies (see Figure 3). All categories are of interest to us, given that they are used to define elements of competencies required in order to teach primary science effectively.

Science PCK 1: Teachers' Pedagogical Design Capacity. Lesson Preparation and Adaptation of Curriculum

Teachers tend to prepare, carry out and evaluate lessons based on their beliefs about what good science education should involve. Thus, teaching starts with selecting and adapting curriculum materials (Forbes & Davis, 2010; Glynn & Winter, 2004; Marble, 2007). Forbes and Davis (2010), among others, use the concept of pedagogical design capacity (PDC) to make clear that teachers mobilise their knowledge, attitudes and beliefs, as well as science curriculum materials, to make pedagogical decisions that accomplish particular instructional goals in light of affordances and constraints of their professional contexts. According to researchers, three factors

Pedagogical design capacity – Lesson preparation and adaptation of curriculum
Science PCK 1-1 Teachers' understanding and response to an individual student's interests, strengths, experiences and needs in order to teach meaningful content and context (taking into account prior knowledge; cognitive developmental stage; learning style; interest and language level, caused by age, gender, socio-economic, cultural and/or linguistic background; formal science lessons and experience
Science PCK 1-2 Teachers' understanding and response to context: time, space, location, materials
Science PCK 1-3 Teachers' understanding and response to aims mentioned in standard documents

Facilitation of scaffolded inquiry
Science PCK 2-1 Teachers' ability to ask students to make their prior ideas explicit
Science PCK 2-2 Teachers' ability to ask (divergent) questions about facts and concepts; and encourage and help pupils to apply this knowledge
Science PCK 2-3 Teachers' ability to ask questions about appropriate use of research skills; and encourage and help pupils to apply this knowledge
Science PCK 2-4 Teachers' ability to stimulate discourse, debate and discussion in small groups about research questions and predictions, answers and explanations
Science PCK 2-5 Teachers' ability to discuss and/or visualise pupils' thinking (including mistakes) to generate class discussion in order to enhance meta-cognitive awareness

Evaluation and assessment
Science PCK 3-1 Teachers' ability to connect new knowledge and understanding to prior knowledge
Science PCK 3-2 Teachers' ability to connect new knowledge and understanding to real life context
Science PCK 3-3 Teachers' ability to connect new knowledge and understanding to the overarching science concepts

Attitudes towards science education
Science PCK 4 Teachers' attitudes towards teaching science
Science PCK 5 Teachers' attitudes towards learners and learning science

Figure 3. Elements of teachers' PCK

must be considered in order to do this successfully: first, the individual pupil's interests, strengths, experiences and needs; second, standard documents; and third, the context (see Figure 3). Several researchers address the topic of adapting science content and science instruction to the prior knowledge, experiences, learning style and interest of pupils. This involves making prior knowledge visible to identify pupils' (alternative) conceptions (Forbes & Davis, 2010; Isabelle & de Groot, 2008; Lee et al., 2004; Williams, Linn, Ammon, & Gearhart, 2004), gaining insight into pupils' general knowledge and its relation to scientific practices, and using these intersections as the basis for instructional practices (Amaral & Garrison, 2006; Cuevas et al., 2005; Weld & Funk, 2005). Teachers who possess a strong understanding of the Piagetian development model of intelligence are more likely to effectively use inquiry-based, learning cycle curricula (Luera, Moyer, & Everett, 2005). Furthermore, teachers who are aware of pupils' cultural and linguistic experiences in relation to science and who are committed to teaching for diversity do not accept inequities as a given condition (Lee et al., 2004, 2009).

A second factor to be considered in selecting and adapting curriculum materials is the aims mentioned in standard documents. To incorporate these successfully, teachers must be aware of national or curriculum standards (Davis, 2005; Glynn & Winter, 2004; Katz et al., 2005; Marble, 2007). On the one hand, these national goals might help the teacher in the search for clearly stated criteria to select content and didactic strategies. On the other hand, teacher might experience the contradiction between effective (inquiry-based) learning, which can be time-consuming, and adherence to standardised test, scheduled on the other (Bhattacharayya et al., 2009). Thirdly, teachers who understand the constraints and limitations of the teaching context are better able to prepare high-quality lessons in which the available time is used most effectively. These constraints involve time, space, location and materials (Davis, 2005; Dietz & Davis, 2009; Howes et al., 2009). Forbes and Davis (2010) found that the adaptations teachers often made to curriculum materials were insertion of new elements and deletion of existing elements, in order to better support inquiry-based science instruction. Inversions, duplications and relocations were rarely used (Forbes & Davis, 2010).

Science PCK 2: Teachers' Instructional Strategies. Facilitating Scaffolded Inquiry

To create and support constructivist learning, teachers need to have sufficient understanding of the pupils' prior knowledge, including their experiences, prior learning and alternative conceptions or non-scientific ideas (Kang, 2007). To gain insight into the pupils' prior knowledge, they can discuss everyday events that pupils have observed and possibly have partial explanations for, thereby encouraging pupils to apply scientific concepts (Shymanski et al., 2004; van Zee et al., 2005). They can also ask pupils to use learned concepts to explain real-life situations before going on to new materials. Competent, experienced teachers see learning science as pupils changing their ideas into ones consistent with scientific concepts by means of learning activities that enable them to construct their own knowledge in synergy with their existing views (Cuevas et al., 2005). Teachers facilitate this process by asking divergent questions, representing and illustrating scientific facts and concepts and stimulating pupils to use these concepts appropriately while performing investigations (Howes et al., 2009; Lee et al., 2009; van Zee et al., 2005; Weld & Funk, 2005). They also facilitate this by giving four types of feedback during classroom discourse: affirmation instruction; responsive questioning (neutral response and follow-up questions); explicit correction and direct instruction; and constructive challenge (Oliveira, 2009). In order to promote student participation and engagement in science inquiry discussions, they can use oral strategies such as (parallel) repetition, figures of speech, colloquial language, humorous comments and rhetorical questions (Oliveira, 2010). In providing opportunities for pupils to explore their ideas and investigate questions, teachers may follow the model of science as practised in the scientific community (Cuevas et al., 2005; Trundle et al., 2007). This model includes having the pupils question and predict; form explanations using evidence; and communicate and justify findings (Dietz & Davis, 2009). With support from their teachers, pupils can take part in small group discussions about research questions and predictions, answers and explanations (Isabelle & de Groot, 2008; van Zee et al., 2005). Dialogic argumentation may help pupils realise that the claims of science are often contested and that knowledge that was once considered reliable can again become controversial (Van Aalst & Truong, 2011). However, pre-service teachers often prefer a whole class discussion, because that is easier to manage than small groups negotiating a question for inquiry (Cavagnetto, Hand, & Norton-Meier, 2011). When pupils are not accustomed to working collaboratively on problems, they might direct their energy into non-productive acting-out behaviour, when teachers' classroom management practises are not supportive (Glynn & Winter, 2004). In effective inquiry-based science lessons, teachers assist pupils in making sense out of the data they collect, offer their pupils' explanations based on evidence, or analyse and evaluate pupils' alternative conceptions (Avraamidou & Zembal-Saul, 2005; Lee et al., 2004). This provides pupils with guided opportunities to discuss their understanding of the reasons for differences and similarities in data (Warwick & Siraj-Blatchford, 2006) using the right concepts, and between their predictions and the evidence. However, Howes et al. (2009) argue that this process does not happen automatically. In their research, teachers stated that helping their students how to do science and learn that they could be scientists were more important than learning specific scientific concepts. Thus, learning to do what scientists do did override concerns about content and learning specific scientific concepts.

Scientific inquiry context coupled with the teachers' divergent questions or visualisations of the pupils' thinking (including mistakes) can enhance meta-cognitive awareness (Liang & Richardson, 2009). Pupils are asked to explain their results using clear lines of evidence and reasoning (Amaral & Garrison, 2006; Dietz & Davis, 2009), and are thereby encouraged to improve their research skills (Katz et al., 2005; Lee et al., 2008).

Science PCK 3: Evaluation and Assessment

The ultimate goal of evaluation and assessment is to stimulate pupils' meta-cognitive thinking. At the end of a science lesson, teachers can stimulate higher-level thinking by asking open, strategic questions and giving pupils the opportunity to raise questions themselves. These questions make pupils reflect on their learning process, and can achieve at least three aims. First, teachers' questions can help pupils create a bridge between their prior knowledge and the new evidence and information they have just acquired (Dietz & Davis, 2009; Isabelle & de Groot, 2008; Kang, 2007; Marble, 2007). Second, pupils can get an idea of how to transfer the acquired knowledge and investigation skills to other situations. By being asked questions, the pupils will become conscious of the reasoning process, which can help them become aware of the general aspects of their thinking and investigating. Teachers can help pupils transfer the newly acquired science concepts from the particular context of the classroom to other situations by asking for examples of applications in the pupils' real-world environment (Amaral & Garrison, 2006; Cuevas et al., 2005; Glynn & Winter, 2004; Weld & Funk, 2005). Finally, pupils are stimulated to connect new knowledge and understanding to the overarching science concepts (Amaral & Garrison, 2006). Teachers can use assessment to make their classroom practice more effective and efficient, by improving the preparation of the curriculum materials (Davis, 2005; Dietz & Davis, 2009; Forbes & Davis, 2010), their instructional strategies (Oliveira, 2009) and by changing their attitudes and beliefs about science teaching and learning (Bhattacharayya et al., 2009; Kim & Tan, 2011).

Science PCK 4 and 5: Teachers' Knowledge of and Attitudes Towards Science Teaching and Science Learners and Learning

A teacher's approach to science teaching is constructed at a deep level. Changing a teaching approach means examining beliefs and being open to a new identity as a teacher and as a learner (Volkmann & Zgagacz, 2004). Beliefs are created in the process of enculturation into a certain group and agreed upon as information that a person accepts to be true. Beliefs endure unchanged unless deliberately challenged (Hubbard & Abell, 2005). Studies have reported that teachers' beliefs and attitudes are connected to their SMK and the pedagogical and didactical skills they decide to apply in practice (Bhattacharayya et al., 2009; Hubbard & Abell, 2005; Kang, 2007; Leonard et al., 2009; Lewthwaite, 2006; Liang & Richardson, 2009). Attitudes stem from beliefs. An attitude is someone's mental state of readiness that has a dynamic influence upon his or her behaviour (Spector, Burkett, & Leard, 2007). In the context of science education, teachers have knowledge of, beliefs about and attitudes towards (1) teaching science; (2) learning and learners of science; (3) the nature of science; (4) themselves as science teachers and (5) developing professionally in order to become better at teaching science. Following the definition of Shulman (1986b) and the categories mentioned by Grossman (1990) and Magnusson et al. (1999), the first two (knowledge of and attitudes towards teaching science and learning and learners of science) are part of teachers' PCK (see Figure 3), the latter three are not (see Figure 4).

Many researchers studied attitudes towards teaching science and the role of a science teacher. Teachers who are enthusiastic about science and science education tend to promote science learning and understanding, and teach science more often compared to those who are negative about science (Weld & Funk, 2005). Three concepts about teaching science and the consequent practice can be found among primary school teachers worldwide. First, science education is viewed by many teachers as acquiring science literacy (Kim & Tan, 2011; Moseley, Ramsey, & Ruff, 2004). These teachers see science teaching as possessing and transmitting knowledge. A second group of teachers believes in giving learners a more active role and thus allowing them the excitement of finding things out for themselves. They perceive scientific inquiry as hands-on, or involving didactic demonstrations, but do not engage pupils in 'minds-on' learning (Lee et al., 2008). A third group of teachers believes in inquiry-based science lessons in which they engage their pupils with a question, have them participate in some kind of investigation and involve them in discussions of explanations derived in part from those investigations (Hubbard & Abell, 2005; Schwarz & Gwekwerere, 2007). However, some teachers believe that teaching

Elements of teachers' attitudes towards science, themselves and professional development

Attitude 1- Teachers' attitude towards (the nature of) science
Attitude 2- Teachers' attitudes towards themselves as science teachers – self efficacy
Attitude 3- Teachers' attitudes towards professional development and becoming better at teaching science

Figure 4. Elements of teachers' attitudes towards science, themselves and professional development

science as inquiry is too complex to implement and manage within classroom practice because of time and material constraints. Others feel that science as inquiry is possible only with above-average pupils and, therefore, do not attempt to integrate inquiry into their regular education classrooms (Britner & Finson, 2005; Smolleck et al., 2006).

Several researchers addressed the topic of beliefs about learners and learning. Teachers differ in seeing pupils as dependent on their teachers or as relatively independent; in seeing them as naturally inquisitive or unmotivated; in understanding the importance (or unimportance) of pupils' prior knowledge and assessment of learning; and in having high or low expectations of their pupils (Dietz & Davis, 2009; Moseley et al., 2004). The researchers argue that teachers should have confidence in pupils' abilities; otherwise they will not have the deliberate intention of making the pupils understand the content. In other words, teachers' beliefs influence their teaching. Often, their practices are congruent with their beliefs and attitude towards pupils.

Avraamidou and Zembal-Saul (2010) conclude that supporting the development of teachers' PCK for scientific inquiry is no simple task; rather it is a difficult and complex activity, which requires the combination and interaction of a variety of learning experiences.

Cluster of Underlying Capabilities 3: Teachers' Attitudes Towards (Nature of) Science; Themselves as Science Teachers and Professional Development

Much has been written about the nature of science. A teacher can take a position on a continuum with two extreme epistemological attitudes: presenting scientific knowledge as given facts or presenting scientific knowledge as competing theories to evaluate in comparison with other ideas (Eick & Stewart, 2010; Ford, 2006; Kang, 2007). Baxter, Jenkins, Southerland, and Wilson (2004) concluded that teachers view science mainly as a product or as a process. Kim and Tan (2011) reported that preservice teachers believed they needed to teach pupils the correct knowledge of science. As such, any teaching tools and activities need to aim at teaching correct scientific concepts, and any derivation from that would be unacceptable. According to these teachers' understanding, practical work challenged or even contradicted their images of good teaching. For that reason, they were reluctant to implement pupil-centred inquiry-based teaching and practiced teaching, which could be characterised as certainty and authority in knowledge.

Guerra-Ramos, Rijder, and Leach (2010) also studied teachers' ideas about scientists and their work, about scientific inquiry and about measurement. Within each of the three topics, teachers displayed views that were quantitatively different in terms of elaboration of ideas. The researchers identified three patterns in teachers' responses: limited, intermediate or extended contextualisation. Teachers with limited contextualisation showed a lack of discrimination and gave unclear examples, or no examples, combined with vague or no references to contextual elements in ideas about science. Teachers with an extended contextualisation, on the contrary, showed more articulated and clearer responses, including discrimination of aspects related to science and inclusion of arguments recognising diversity and complexity in ideas about science. Several studies have reported that teachers' epistemological understandings are connected to teaching practices (Kim & Tan, 2011; Lee et al., 2004).

Beliefs about one's self and one's role are based on outcome expectancy beliefs and self-efficacy beliefs. A low level of confidence among teachers about their own science teaching abilities (self-efficacy beliefs) has been well established by research (see for example Bhattacharayya et al., 2009; Dietz & Davis, 2009; Lee et al., 2004; Lewthwaite, 2006; Liang & Richardson, 2009; Luera & Otto, 2005; Spector et al., 2007; Weld & Funk, 2005). The impact of teachers' confidence on pupils' learning opportunities has also been shown by research. High levels of confidence may positively influence teachers' decisions to attend professional development sessions; devote the time necessary to ensure they are actively pursuing the professional development agenda and persevere when faced with a challenging situation (Lewthwaite, 2006). Jung and Tonso (2006) showed that teachers' confidence in their own ability to teach science has a positive impact on their effectiveness and behaviour. Lack of confidence, on the other hand, might lead a teacher to limit time spent on science, select specific content themes, restrict classroom activities to simply 'following instructions' and inhibit creativity and questioning. Kim and Tan (2011) also reported that (pre-service) teachers with a limited repertoire of teaching strategies were vulnerable to not being ready or confident enough to deal with unexpected results that may appear during inquiry-based science lessons. This contributed to their anxiety and discouraged them from conducting practical work. Other teachers use coping strategies that enable them to influence their pupils' understanding, while enhancing their own conceptions, such as listening to their pupils and studying science literature.

The above-mentioned aspects of attitudes towards science, science teaching, science learners and learning (see Figure 3) and self-efficacy in teaching science influence the teacher as a learner (see Figures 4 and 5). Several professional development programmes start with a focus on the teachers' current perceptions of themselves as teachers, in order to plan a path towards a goal for the future. This encompasses the image of teachers as potential role models or exemplars of practice (see for example Dietz & Davis, 2009). Epistemological beliefs about science and beliefs about good science teaching might also be an important part of training (Choy & Ramsey, 2009; Kang, 2007).

Most teachers believe that experience, theory or a mixture of both, combined with reflection, helps them to be better teachers (Moseley et al., 2004). Some teachers see learning to teach science as a lifelong process, while others view it as something that can be learnt in a limited period of time or never learnt at all—the latter are those, for example, who see themselves as 'not the science type' (Moseley et al., 2004; Weld & Funk, 2005). This belief of being able (or unable) to learn science and science teaching is dynamic and can be influenced by experiences and guided reflection (Luera & Otto, 2005; Spector et al., 2007). Personalisation of science inquiry experiences helps teachers and student teachers realise that they can teach science, use scientific habits of mind and become sensitised to the role of inquiry in solving everyday problems. Approaches that address teachers' perceived problems of practice and serve as a bridge between reform-based goals and pre-service teachers' own goals and practices appear to advance the teachers' PCK (Schwarz, 2009). Becoming aware of using scientific habits of mind can help teachers and student teachers see that teaching science is similar to what they already can do. Helping them become reflective practitioners develops their self-efficacy regarding their ability to teach science and empowers them to teach science using inquiry.

Beliefs can persist even when, logically, they should not. Because teachers invest emotionally and intellectually in their beliefs, they seek to maintain them unless these beliefs are adequately challenged. Since each new experience is filtered through the lens of prior belief, individuals may turn conflicting evidence into support for their beliefs. Thus, the problem for teacher educators is to challenge firmly held beliefs that are often in conflict with the best practice literature (Hubbard & Abell, 2005). Kang (2007) suggests that there is need for long-term support for teachers' learning about conceptual change. Teaching experience does not necessarily bring expertise in science teaching for conceptual learning, thus pointing to the importance of providing ongoing professional development to stimulate teachers' connecting their experience to educational theory and research and teaching for conceptual learning in particular.

Connected Competencies

Elements of competencies, as described above, are connected in complex ways. Several researchers assert that teachers' high level of well-connected SMK has a positive influence on their pedagogical and didactical skills related to science (Lee et al., 2009). A well-organised SMK base also affects a teacher's interest in science (Leonard et al., 2009) and their self-efficacy beliefs (Bhattacharayya et al., 2009; van Zee et al., 2005). Higher self-efficacy beliefs contribute to teachers' motivation, commitment to student achievement and teaching performance (Liang & Richardson, 2009). Teachers with a higher self-efficacy also employ inquiry-based methods easier and more effectively in practice (Lee et al., 2009; Luera & Otto, 2005). Furthermore, attitudes towards teaching and learning science are expressed in whether or not teachers implement reform-based curricula (Eick & Stewart, 2010). Curiosity towards science can be a foundation for an investigative approach to learning (Leonard et al., 2009; van Zee et al., 2005) and teaching science (Eick & Stewart, 2010). However, Liang and Gabel (2005) could not find significant differences in attitudes towards science teaching between prospective teachers with strong content knowledge and those with weak content knowledge. It appeared that the learners' attitudes were influenced by multiple factors, such as their past science learning experiences, the perceived relevance of science to them personally and the discrepancy between the actual and their preferred learning environment. Their classroom practice was influenced not only by content knowledge but also by perceptions of what a good teacher is, of themselves as teachers, of science experiences and of the nature of science.

Research efforts to understand and reduce the complexity of teaching as well as to represent relationships between several teaching competency elements and enacted practice have generated a variety of models. Gess-Newsome (1999) visualised two models, which can be placed on a continuum. On one end, there is the so-called integrative model of teacher in which PCK does not exist and teacher knowledge can be explained by the intersection of three constructs: SMK, pedagogical knowledge and contextual knowledge. Teaching, then, is the integration of these three domains.

On the other end, PCK is seen as the synthesis of all knowledge required to be an effective teacher. In this perspective, PCK is the transformation of subject matter, pedagogical and contextual knowledge into a unique form that impacts teaching practice. Whether teacher knowledge is a compound as in the transformative model or a mixture as in the integrative model has implications for the definition of teaching expertise and competencies; identification and development of competency clusters and competency elements; and concrete implications for teacher preparation both in initial education and post-graduate training. In the transformative model, teachers possess PCK for all topics taught. PCK must be well structured and easily accessible for application. Following the integrative model, the knowledge bases of SMK, pedagogy and context are developed separately, but can best be integrated in the act of teaching. Based on this latter model, teachers are fluid in the active integration of knowledge, and knowledge bases can be taught separately or in a more integrated way. In both cases, teaching experiences are seen as reinforcing the professional development of teachers through the selection, integration and use of the knowledge bases, while in the integrative perspective, reflection on and in practice is also perceived as a source of professional development.

Since SMK and attitudes towards science and science teaching have a nurturing and reciprocal relationship with science PCK and enacted practice, we perceive PCK as a separate cluster, as in the transformative model. At the same time, there is evidence and support for separately developed clusters (attitude, SMK and PCK), which are integrated in practice. Based on our literature study, we combined the two perspectives discussed above and embedded them in context (see Figure 5). Teacher competence is not fixed and in existence external to teachers. Their competencies influence one another and develop, stabilise or decline in a historical, cultural and organisational context.

The American National Science Education Standards

The American NSES (NRC, 1996) outlines what knowledge and skills are needed for scientific erudition at different grade levels. It describes an educational system in which all pupils demonstrate high levels of performance and all teachers have sufficient knowledge to create powerful learning environments. The document presents a vision of communities of teachers and pupils who are focused on learning science and supported by educational programmes and systems that foster achievement.

The intention of the document is to establish science standards for all pupils. The standards are based on the premise that pupils cannot achieve high levels of performance without access to skilled professional teachers, adequate classroom time, a rich

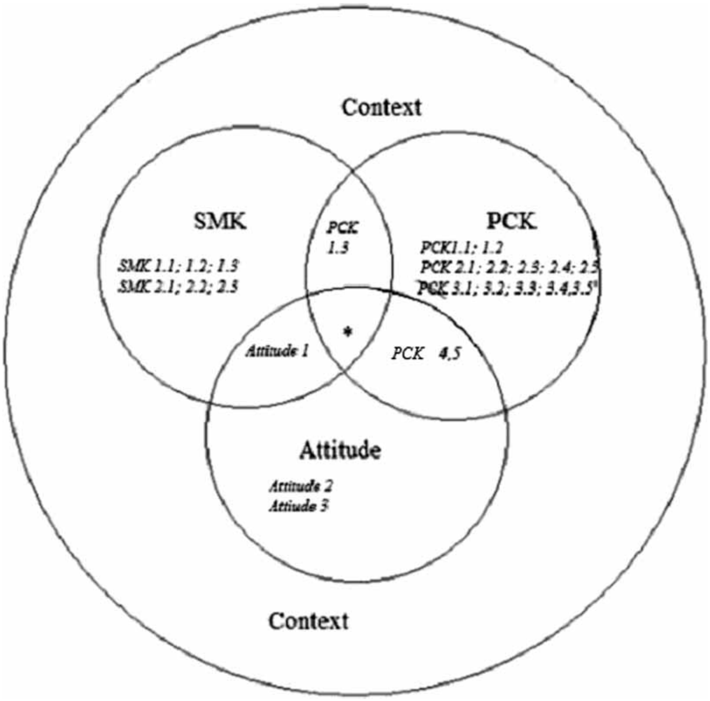

Figure 5. Competence-based model of inquiry-based science teaching competencies.
Note: *Enacted practice

selection of learning materials, accommodating work spaces and the resources of the communities in which their schools are located. Learning science is seen as something that pupils do, not something that is done to them. 'Hands-on' activities, while essential, are perceived as not enough. Pupils must have 'minds-on' experiences as well. Inquiry is believed to be central to science learning, and it is one of many different strategies that teachers need to use to develop their pupils' understanding and abilities to the required level. The standards provide criteria that people at the local, state and national levels can use to judge whether particular actions will serve the vision of a scientifically literate society. The aim is to bring co-ordination, consistency and coherence to the improvement of science education. The standards are divided into six categories: science teaching; professional development for teachers of science; assessment in science education; science content; science education programmes and science education systems.

The specific standards for science teaching describe what teachers of science at all grade levels should know and be able to do. They are divided into six areas as described in the box below (Figure 6).

Standards for professional development activities and goals involve learning science content through inquiry; integrating knowledge about science with knowledge about learners, pedagogy and pupils; and developing the understanding and ability for lifelong learning.

American National Science Education Standards: Science teaching

A. Teachers of science plan an inquiry-based science program for their students. In doing this, teachers:

Develop a framework of year-long and short-term goals for students; Select science content and adapt and design curricula to meet the interest, knowledge, understanding, abilities, and experiences of students; Select teaching and assessment strategies that support the development of student understanding and nurture a community of science learners; Work together as colleagues within and across disciplines and grade levels.

B. Teachers of science guide and facilitate learning. In doing this, teachers:

Focus and support inquiries while interacting with students; Orchestrate discourse among students about scientific ideas; Challenge students to accept and share responsibility for their own learning; Recognize and respond to student diversity and encourage all students to participate fully in science learning; Encourage and model the skills of scientific inquiry, as well as the curiosity, openness to new ideas and data, and scepticism that characterize science.

C. Teachers of science engage in ongoing assessment of their teaching and of student learning. In doing this, teachers:

Use multiple methods and systematically gather data about student understanding and ability; Analyze assessment data to guide teaching; Guide students in self-assessment; Use student data, observations of teaching, and interactions with colleagues to reflect on and improve teaching practice; Use student data, observations of teaching, and interactions with colleagues to report student achievement and opportunities to learn to students, teachers, parents, policymakers, and the general public.

D. Teachers of science design and manage learning environments that provide students with the time, space, and resources needed for learning science. In doing this, teachers:

Structure the time available so that students are able to engage in extended investigations; Create a setting for students work that is flexible and supportive of science inquiry; Ensure a safe working environment; Make the available science tools, materials, and technological resources accessible to students; Identify and use resources outside the school; Engage students in designing the learning environment.

E. Teachers of science develop communities of science learners that reflect the intellectual rigor of scientific inquiry and the attitudes and social values conducive to science learning. In doing this, teachers:

Display and demand respect for the ideas, skills, and experiences of all students; Enable students to have a significant voice in decisions about the content and context of their work and require students to take responsibility for the learning of all members of the community; Nurture collaboration among students; Structure and facilitate ongoing formal and informal discussion based on a shared understanding of rules of scientific discourse; Model and emphasize the skills, attitudes, and values of scientific inquiry.

F. Teachers of science actively participate in the ongoing planning and development of the school science program. In doing this, teachers:

Plan and develop the school science program; Participate in decisions concerning the allocation of time and other resources to the science program; Participate fully in planning and implementing professional growth and development strategies for themselves and their colleagues.

(National Research Committee, 1996, p. 28; 30; 32; 37-38; 43; 45-46; 51)

Figure 6. American national science teaching standards

The standards for science content are divided into unifying concepts and processes in science; science as inquiry; physical science; life science; earth and space science; science and technology; science in personal and social perspectives; history and nature of science.

Research Synthesis

In this section, we first summarise research findings of our literature review; then compare results of literature review with the American Science Teaching standards; third discuss the applicability of the American standards to the Dutch and European context; fourth reflect on the use of competence concept, fifth mention strength and weaknesses of this research and finally present implications for future practise and future research.

This article contributes to a theory of required competencies for inquiry-based science teaching. We found 22 elements of competencies for inquiry-based science teaching and divided them into the following clusters of competence underlying capabilities: SMK; science PCK and teachers' attitudes towards themselves as science teachers and towards professional development (see Figure 5). To retrieve and transfer relevant information to appropriate situations teachers need well-connected and well-organised knowledge (Luera & Otto, 2005). Learning to teach inquiry-based science also involves clarifying, confronting and expanding one's ideas, beliefs and attitudes about science teaching and learning (Moseley et al., 2004; Volkmann & Zgagacz, 2004). Apart from strong SMK and a positive attitude towards (teaching and learning) science, teachers need knowledge that blends subject matter and pedagogy (Davis, 2005). Science PCK, as part of the science teaching competencies, helps teachers recognise that the knowledge required to teach science is different from the knowledge needed to teach other subjects. The danger with the PCK construct is that it could be seen as objectifying teaching so that the development of teachers' SMK, self-confidence and decision-making skills might be overlooked (Nilsson, 2008).

Comparison of Literature Review Results and American National Science Education Standards

Several of the standards for science teaching correspond to competence elements dealing with PCK extracted from the articles. As mentioned above, 'PDC: lesson preparation and didactical skills and knowledge' (i.e. science PCK1) exists out of three aspects. The first 'teachers' understanding and response to individual needs' is similar to aspects of teaching standard A, that is to 'select science content and adapt and design curricula to meet interests, knowledge, understanding, abilities and experiences of students' as well as to aspects of standard E: 'Display and demand respect for the ideas, skills and experiences of all students'.

The second element of PCK, teachers' understanding and response to context: time, space, location, materials resembles aspects of standards D ('Teachers of science design and manage learning environments that provide pupils with the time, space and resources needed for learning science') and aspects of standard F ('Participate in decisions concerning the allocation of time and other resources to the science programme').

The third element of PCK 1, 'teachers' understanding and response to aims mentioned in standard documents' might correspond with elements of standard F 'Plan and develop the school science programme' although in the American Standard no limits are given by a prescribed national curriculum. In 2003, these were made more concrete, by the National Science Teachers Association position statements of 2003, where goals for each level of education were proposed.

'Facilitation of scaffolded inquiry' (Science PCK 2) matches teaching standards B ('Teachers of science guide and facilitate learning') and D ('Teachers of science design and manage learning environments that provide pupils with the time, space and resources needed for learning science'). Science PCK 2–1 'teachers' ability to ask students to make their prior ideas explicit' is a way to 'recognise and respond to student diversity and encourage all students to participate fully in science learning'. Science PCK 2–2 'teachers' ability to ask (divergent) questions about facts and concepts; and encourage and help pupils to apply this knowledge' is a method to 'recognise and respond to student diversity and encourage all students to participate fully in science learning' as well as a way to 'encourage and model the skills of scientific inquiry, the curiosity, openness to new ideas and data, and scepticism that characterise science'. Science PCK 2–3 'teachers' ability to ask questions about appropriate use of research skills; and encourage and help pupils to apply this knowledge' resembles 'focus and support inquiries while interacting with students'. Science PCK 2–4: 'teachers' ability to stimulate discourse, debate and discussion in small groups about research questions and predictions, answers and explanations' is comparable to 'orchestrate discourse among students about scientific ideas'. Science PCK 2–5 'teachers' ability to discuss and/or visualise pupils' thinking (including mistakes) to generate class discussion in order to enhance meta-cognitive awareness is a way to 'challenge students to accept and share responsibility for their own learning'.

'Evaluation and assessment' (Science PCK 3) is similar to teaching standard C ('Teachers of science engage in ongoing assessment of their teaching and of student learning'). Finally, one element of teachers' attitudes, namely, 'attitude towards professional development' is partly reflected in standard F ('Teachers of science actively participate in the ongoing planning and development of the school science programme') while the majority of this capability is not described under the teaching standards but in a separate chapter on professional development for teachers of science.

The attitudes of teachers towards science learning are reflected in standard E: 'Teachers of science develop communities of science learners that reflect the intellectual rigour of scientific inquiry and the attitudes and social values conducive to science learning. In doing this, teachers model and emphasise the skills, attitudes and values of scientific inquiry'. The attitudes of teachers towards science teaching (science PCK 4) are not mentioned explicitly in the American teaching standards, whereas these aspects of science PCK appeared repeatedly in our literature review.

Finally, teachers' attitudes towards themselves as science teachers (self-efficacy) and towards science are also missing in the American standards, while our review indicated that this aspect is interwoven with other science teaching competencies.

Applicability of American Standards in the Contemporary Dutch and European Context

We can conclude that the majority of the teaching-related American NSES are similar to the elements of teacher competencies found in the reviewed literature. Moreover, both the articles and the American standards emphasised the importance of research skills and competencies in the SMK of teachers.

Our research indicates that the American standards do not mention teachers' attitudes towards themselves as science teachers or their attitudes towards science and science teaching explicitly. We advise that these elements be added, since they do have an impact on teaching practice. This might encourage teacher educators to focus on these aspects and help primary school teachers reflect on their attitudes and gain insight into what helps or hinders their professional development.

Finally, the American standards are presented in a summative way. However, our research indicates that the competencies should be presented in an integrated and holistic way.

The gain of this study is that we can understand our own Dutch situation better, by getting some insight into the situation of USA. Success of implementing the revised American standards in the Dutch context depends on quality and innovative capacity of teacher training institutes, political, economical and cultural factors of the country. All professionals involved have to look for the best opportunities to take action and have effect (Abell, 2000). The question remains, can the outcomes be transferred to the context of Europe, despite the differences between the countries. To a certain extent European researchers and politicians can learn from their US colleagues concerning standardisation of inquiry-based science teaching. For now, all European countries either have their own competence profiles or lack these documents. Convergence of competence profiles opens the opportunity to enhance co-operation between institutes in several European countries. On the other hand, there might also be a risk of standardisation. In some European countries, competencies are viewed as discrete tasks, identified by functional analysis of work roles and do not take into account the context in which the competencies are applied. Because of the complexity and indeterminate nature of real-world situations, behavioural objectives can never be achieved in practice with the precision they offer in theory. The narrow competence approach might not help but even hinder improvement of the European science education, since research on implementation of innovations shows that success of innovations depends for a greater part on the attitude of those involved. We should recognise the connections between tasks; the meaning, intention and attributes that underlie performance of teachers; the effect of interpersonal and ethical aspects; and the context of performance. Standardisation of a competence profile might improve European science education by increased collaboration of researchers and exchange of teachers and teacher educators between countries, despite variations of educational systems and society. We agree with Abell (2000) that although we must think globally (or continental) about the issues and values in science education, we must act locally to affect our particular context.

Reflections on the Use of Competence Concept

The competence concept makes it clear that there are reciprocal relationships between the components, and that professional development of teachers in primary science education is a process of growth in applying a complex and contextualised set of competencies to specific problems in practice. It also illustrates that learning to teach science is not about acquiring a certain number of tricks based on a set of general pedagogical strategies, rewarded with a certificate at the end of that process. Knowledge and beliefs about science teaching and learning guide a teacher's instructional decisions about what content to teach, which instructional strategies and didactic materials to use, which assessment of pupils' learning to apply. Reflection during and on the science lesson can in turn confirm or change a teacher's underlying beliefs and knowledge life long.

In order to construct a teacher competence profile for primary level inquiry-based science teaching, we adopted Mulder's (2007) definition of competence as 'the integrated set of knowledge, attitudes and skills of a person' (Mulder, 2007) 'having a strong relationship with organisational effectiveness' (Mulder et al., 2006). This concept was helpful in finding sources that on the one hand provided insight into several aspects of inquiry-based science competencies and on the other hand were homogeneous enough to result in convergent findings. We found that elements of competencies are connected in complex ways. Several researchers assert that teachers' high level of well-connected content knowledge has a positive influence on their pedagogical and didactical skills related to science (Lee et al., 2009). Therefore, we suggest that the role of science PCK as part of teaching science and the role played by teachers' beliefs and attitudes in influencing their practice should be made more explicit in both the text and the organisation of the science education standards. A non-linear, holistic, competence-based model can confront the separation and fragmentation of knowledge, skills and attitude and challenges its consumptions. Furthermore, a non-linear model can emphasise the dynamic character of education in which the teacher should have a pro-active attitude, taking into account the needs of the pupils and society as a whole. The use of hypertext and multimedia tools might facilitate a dynamic, representative model of connected, underlying capabilities of science teaching competencies.

Strength and Weaknesses of the Study

One strength of this research is the systematic way in which it was conducted. Rather than using just one database, two were searched and the findings compared to obtain a larger and more varied set of articles. The keywords used to search for articles were logically derived from the definition of competence. We limited our search and analyses to the preceding seven years (2004–2011), because inquiry-based education is changing rapidly. The use of current publications minimised the risk of including articles based on an out-of-date concept of inquiry-based education and related inquiry-based competencies, or in which competencies are seen as fragmented and isolated aspects of behaviour. Another strength is that through literature analysis and synthesis several elements of competencies were brought together and the relationships between these elements and between clusters of competencies were made explicit. A weakness of the literature study might be that all articles were treated equally, despite differences in the qualitative and quantitative methods of research applied and despite differences in the size of the respondent groups. We did not limit the size or kind of studies to be considered in our analysis, in order to find as many elements of competencies as possible and to be able to compare and look for commonalities in different studies.

Implications for Future Practice

Since the elements of competencies required to teach science successfully are so closely related, a teacher's strength or weakness in one may affect his or her mastery of others, and consequently classroom practice and student performance and success. In other words, the whole is more than the sum of its parts. This conclusion suggests that behavioural functionalism, in which skills training is seen as a way to acquire isolated teaching competencies, is not enough (Mulder et al., 2006). There is a need to go beyond only lecturing teachers on how to teach science and how to become science teachers (Moseley et al., 2004). Teachers have to also understand and respond to individual pupils' needs and to context variables such as available time, space, location and materials. Thus, even the integrated occupational approach, in which knowledge, skills and attitude are taught and learnt simultaneously, is not sufficient in preparing pre-service teachers for their future role. In order to learn, master and apply inquiry-based science teaching competencies in practice, situated professionalism might be the answer (Bhattacharayya et al., 2009). Instructional approaches, which merely advocate inquiry-based teaching without providing direct experience, seem to be insufficient and contrary to inquiry-based learning (Britner & Finson, 2005). From this point of view, competencies are mastered through integrated application in the classroom. It is important for pre-service teachers to build a strongly connected science content knowledge base as well as confidence during their initial studies. Teacher educators need to provide opportunities for pre-service teachers to examine, elaborate and integrate new knowledge and beliefs about teaching and learning into their existing knowledge and beliefs. If teacher training fails to help them build confidence, they might remain unfamiliar and uncomfortable with teaching inquiry-based science when they enter teaching professionally (Liang & Richardson, 2009). Exposure to effective science inquiry models in student teaching programmes might partly tackle this problem, but it may not be enough to change the knowledge and beliefs of pre-service teachers. If student teachers only copy 'activities that work' (Appleton, 2002) they may end up teaching a fragmented curriculum; providing pupils with insufficient or inappropriate background information; and considering activities as isolated experiments with a predictable outcome, rather than adopting a (socio-) constructivist view, in which (collective) knowledge making is seen as the central point. To learn to implement the inquiry method, pre-service teachers need mentoring and support within the context of their internship (Moseley et al., 2004) and induction period as a starting teacher (Avraamidou & Zembal-Saul, 2010). Strong partnerships between teacher training institutions and primary schools might contribute to achieving this goal. Pre-service teachers can also gain SMK and PCK by studying independently or in post-academic courses; by reflecting on the images of inquiry within curriculum materials and within educational practice to add ideas to their repertoires, by integrating those ideas with others and by further developing their own identities as teachers (Dietz & Davis, 2009; Park Rogers, 2009). This could help reduce the anxiety often associated with teaching science (Moseley et al., 2004) and could address the concern of Appleton (2002) that only 'activities that work' will be implemented in science lessons.

Discussions or assignments that encourage reflection among pre-service elementary school teachers might help teacher educators gain insight into what pre-service elementary teachers know about inquiry-based science teaching, what they think about it and what challenges they face in practice. Such an explicit and reflective approach could help teacher educators adapt the lessons of teacher training colleges to the needs of students.

Implications for Future Research

Discrepancies exist between what is recommended for inquiry-based science education and what is actually happening in practise (Kim & Tan, 2011; Vikström, 2008). Researchers have to consider and understand why teachers have not been using practical examples of inquiry regularly. Such understanding should then have an effect on research on classroom practice and the professional development of teachers. Explanations may lie in differences in how teachers and researchers perceive inquiry-based science education. Reducing the cultural barriers that hinder communication between science researchers, science lecturers in teacher training college and teachers is also an important task for policy-makers and for members of these communities, to be able to develop suitable and effective professional development and engagement systems.

More research is needed to further explore and develop common ground concerning inquiry-based education and required competencies, to gain insight into the relationships between different teaching competencies and their underlying capabilities, and to gain knowledge about the factors influencing the effectiveness of professional development programmes. Teacher involvement in teacher preparation is essential. Teachers need a voice in the new establishment of new teacher entry standards and entry courses. Stakeholders, including teachers, should come together in context-specific groups (in terms of geographic location and targeted level of education) to find commonalities in their understanding of inquiry-based education and, ultimately, to define required teacher competencies. In further research, we will involve teachers, policy-makers and researchers in a discussion of specific primary school science education competencies for the Netherlands. We will conduct a Delphi study to examine whether the 22 selected elements of competencies related to SMK, attitudes and PCK are considered by experts to be sufficient to teach science effectively. Sequential questionnaires interspersed with summarised information and feedback derived from earlier responses will be used to develop an accurate, validated shared set of competencies.

Further studies are needed to gain more insight into the relationships between the clusters of underlying capabilities and the elements of competencies. So far, we have only found a limited number of studies about the relationships between SMK and didactical skills, between attitude and classroom practice and between SMK and attitude toward science teaching. It will be interesting to see how the elements of Science PCK, SMK and attitudes grow over time as pre-service teachers advance and progress through their careers.

Furthermore, only limited research has been conducted to discover how professional development programmes can be most effective in helping students acquire inquiry-based science teaching competencies. Further research is recommended to illustrate specific characteristics and components of effective teacher education programmes that contribute to the development and use of teacher Science PCK. The following questions would therefore be interesting for future research. How do beginning teachers employ compensatory strategies to make up for their limited knowledge? What is the optimal set of experiences which will both inspire and enable teachers to be effective in inquiry-based science teaching? How do SMK, science PCK and attitudes influence each other? How can primary teachers develop science-related competencies in addition to (or in combination with) the many other competencies needed for teaching other subjects? Is the process of becoming an expert in science teaching a gradual, continuous and never-ending process or are there certain experiences in teachers' careers which are critical and a motor of sudden change in teachers' beliefs, attitude, knowledge and practices?

Longitudinal studies of multiple cases should allow researchers to understand teachers' growth and the sources of growth of a teachers' competencies over time. Such research might be able to identify the variety of factors and conditions that help or hinder teachers in acquiring inquiry-based science teaching competencies and implementing inquiry-based teaching and learning in the classroom.

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