Teaching Electromagnetism for the First Time: a Case Study of Pre-service Science Teachers' Enacted Pedagogical Content Knowledge

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Abstract

This paper reports on topic-specific pedagogical content knowledge (PCK) enacted by three pre-service science teachers during their final year school-based internship. An interpretive, qualitative case study was conducted to investigate to what extent the pre-service teachers applied the knowledge taught during a preceding physical science method course, when teaching electromagnetism for the first time. The study is rooted in the revised consensus model of PCK with focus on the enacted PCK (ePCK) of pre-service teachers. Five topic-specific PCK components informed the design of an ePCK rubric used to assess the extent to which the pre-service teachers' PCK manifested in their practice. Data were captured by written content representations (CoRes), lesson observations and interviews. The rubric, together with further qualitative analysis, was used to determine how the pre-service teachers translated the knowledge taught during training into practice. Findings indicate that the participating pre-service teachers enacted certain components of the taught PCK and reasoned pedagogically about their teaching, though not at the same level for all main ideas in the topic. After teaching the topic, the pre-service teachers indicated that they would like to improve their sequencing of key concepts. It was concluded that the teaching experience contributed to a better understanding of conceptual teaching strategies. The findings of the study may inform PCK development in teacher education.

Keywords: Enacted PCK; Pre-service science teacher development; Teaching electromagnetism

Introduction

Experts in the field of PCK suggest that an important argument for studying pedagogical content knowledge (PCK) is that teachers with higher levels of PCK are more competent in supporting students to learn (Kirschner et al. 2015). It is therefore reasonable to assume that teacher education needs to concentrate on ways to capture and develop the PCK of student teachers. During training pre-service, teachers should learn to think about their content knowledge as a construct in need of transformation for teaching rather than knowledge they possess for pure intrinsic value (Geddis 1993). Transformation of teacher's content knowledge (CK) results in PCK (Shulman 1987). Although the development of PCK is a lifelong process, teacher education should be an important starting point (Friedrichsen et al. 2009), and a valuable arena for this development is the teaching practicum (Nilsson and Loughran 2012).

Alonzo et al. (2012) argued that the knowledge teachers have, but do not enact, is higly unlikely to have and effect on learners' conceptual development. To understand the relationship between knowledge and practice, Alonzo and Kim (2016) used the constructs declarative PCK, which includes, but is not restricted to paper-and pencil methods to capture PCK and dynamic PCK which refers to instances where PCK is being demonstrated during teaching. They noticed that teachers' dynamic PCK relied heavily on their declarative PCK. Mazibe (2017) also distinguished between enacted PCK and the PCK captured with paper-and-pencil methods, called reported PCK and found that teachers tend to enact PCK at a lower level than their reported PCK. In line with this reasoning, Park and Suh (2015) highlight the importance of establishing how teachers translate their PCK into practice and the difference between the PCK of teachers who 'enact quality teaching' and those who do not. As such, studying the enactment of PCK of pre-service teachers after training in relation to what was taught during training may inform the design of pre-service teacher education.

A salient feature of recent literature on different aspects of PCK in science teacher education is that CK about a specific topic and its PCK are often studied in tandem. PCK has been explored in topics such as the solar system (Henze et al. 2008), chemical equilibrium (Mavhunga and Rollnick 2013) and organic chemistry (Davidowitz et al. 2014). However, there is a paucity of studies done on the PCK of teachers teaching electromagnetism, even though it is an integral part of school curricula worldwide, including South Africa (DBE 2011). In addition, it is has been reported that students and teachers regard electromagnetism as a difficult topic (Dori and Belcher 2005; Sağlam and Millar 2006). Therefore, we argue that a study of PCK in electromagnetism would add new knowledge to the field.

Thus, this paper focusses on pre-service teachers enacting PCK about electromagnetism while teaching the topic for the first time during their placement at schools in their final year of study. It emerges from a broader study that explored the development of pre-service science teachers' PCK as a result of explicit instruction in five identified components of topic-specific PCK (Mavhunga 2014) for teaching electromagnetism. The instruction took place as part of a physics method course which was similar to one carried out by Mavhunga (2018). This training entailed learning to transform content knowledge by reasoning through the five content-specific components of topic-specific PCK.

The study was guided by the following question: How do pre-service teachers enact topic-specific PCK about electromagnetism when teaching the topic for the first time?

Literature Review

Electromagnetism as a Curriculum Topic

In South Africa, electromagnetism is prescribed as a grade 11 physics topic by the government's Curriculum and Assessment Policy Statement (CAPS) (Department of Basic Education 2011). Grade 11 students are approximately 17 years of age. The CAPS specifies when topics should be taught, the time to be spent per topic and recommended and prescribed practical activities. Teachers are expected to adhere to the guidelines and the sequencing of topics since high-stakes national assessments are based on CAPS.

In this study, electromagnetism was selected to explore the PCK of pre-service teachers, as it is generally regarded as a difficult topic to teach and to understand, mainly because of its abstract nature (Dori and Belcher 2005). A study conducted by Hekkenberg et al. (2015) showed that teachers' confusions about electric and magnetic fields are comparable with those of secondary school learners. This emphasizes the need to teach pre-service teachers about the misconceptions and confusions learners have in a co-attempt to address the misconception they have themselves. Education of pre-service teachers about concept confusions and misconceptions in electromagnetism falls within the framework of this study.

A recent study on high school learners' reasoning about electromagnetism (Jelicic et al. 2017) confirmed that learners find the topic challenging that they have deeply rooted misconceptions and use unscientific models to explain electromagnetic phenomena. One misconception influencing learners' thinking about many aspects of electromagnetism is the idea that 'magnetic poles are charged', which is linked to the general confusion between electric and magnetic fields (Maloney et al. 2001). This may lead to the belief that magnetic poles exert forces on charges, whether the charges are moving or not. Maloney et al. (2001) also report on challenges to differentiate between the changes in magnetic flux as opposed to its mere presence. According to Zuza et al. (2014), many science students see magnetic flux as the 'flow' of the magnetic field, which can be associated with Sağlam and Millar's (2006) observation of the erroneous idea that magnetic field lines indicate the 'flow' or 'movement' of the magnetic field. Thus, teaching electromagnetism necessitates a clear understanding of the topic and unique teaching strategies in terms of the components of topic-specific PCK outlined below, which includes understanding the sequencing of ideas, common misconceptions and use of representations to address concepts that are abstract and unfamiliar. This paper deals with two main concepts in electromagnetism prescribed by CAPS; the magnetic field around a current-carrying conductor and Faraday's law.

PCK as a Topic-Specific Construct

PCK, a central part of teacher knowledge, is a complex construct consisting of distinguishable but inseparable components. Shulman (1986) suggests that teacher knowledge consists of: (a) subject matter content knowledge, (b) pedagogical content knowledge and (c) curricular knowledge. Veal and MaKinster (1999) developed a hierarchical general taxonomy of PCK and a taxonomy of PCK attributes. The taxonomy ranges from pedagogy in its broadest sense, through PCK at discipline specific level (e.g.

science), domain-specific PCK (e.g. physics), to topic-specific PCK at the most specific level, such as electromagnetism in physics. In many instances, studies conducted on science teacher professional development (Davidowitz and Potgieter 2016) and improving science teachers' PCK (Mavhunga 2014; Mavhunga and Rollnick 2013) indeed focussed on only one particular topic in the subject chemistry. Such studies in physics topics do not abound. In the studies mentioned above, five knowledge components from which transformation of the CK emerges were identified as:

Curricular Saliency

Knowledge that enables a teacher to select and sequence key concepts for the understanding of the topic.

Learner Prior Knowledge

Knowledge that enables teachers to relate their teaching to what learners already know from previous instruction or personal experiences, including both correct and alternate conceptions as documented in literature.

What Is Difficult to Teach

Knowledge of concepts that need dedicated attention when teaching ideas that learners usually find difficult to understand.

Representations Including Analogies

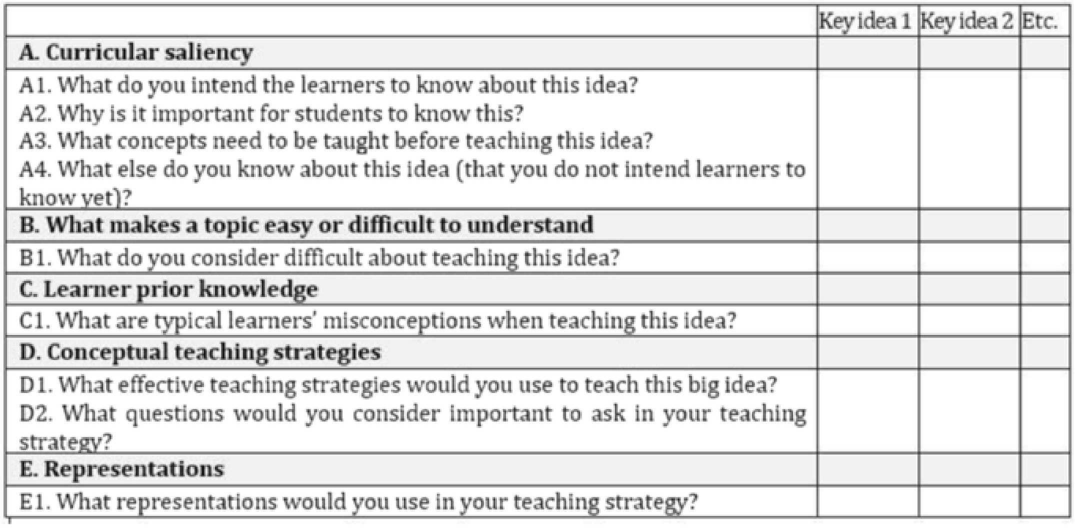
Knowledge of ways of representing the content in ways that support the conceptual development of ideas, including analogies, demonstrations, diagrams, models and computer simulations.

Conceptual Teaching Strategies

Knowledge of topic-specific instruction encompassing knowledge, competence and fruitful integration of all the abovementioned components.

Since teaching is an action, it is important that studies about PCK venture into the exploration of the relationship between knowing (both CK and PCK) and acting (Henze and Van Driel 2015). A content representation (CoRe) developed by Loughran et al. (2004) is a valuable and practical tool to capture the knowledge of a teacher about a certain science topic and the teaching of that topic. The CoRe tool consists of eight prompts, organised in tabular format that elicits teachers' understanding of specific content and the teaching thereof. The headings of the columns in the instrument are key ideas or main concepts that underpin the understanding of the particular science topic and the rest of the prompts are completed with reference to these ideas. Thus, CoRes constructed by an individual give a qualitative picture of the person's knowledge about the content and the teaching of a specific topic.

A notable parallel can be seen between the prompts in the CoRe tool developed by Loughran et al. and the five components of topic-specific PCK, listed before, and this leads to an adaptation of the CoRe (Fig. 1) by Rollnick and Mavhunga (2016) to cohere with these five components.



	Key idea 1	Key idea 2	Etc.
A. Curricular saliency			
A1. What do you intend the learners to know about this idea? A2. Why is it important for students to know this? A3. What concepts need to be taught before teaching this idea? A4. What else do you know about this idea (that you do not intend learners to know yet)?			
B. What makes a topic easy or difficult to understand			
B1. What do you consider difficult about teaching this idea?			
C. Learner prior knowledge			
C1. What are typical learners' misconceptions when teaching this idea?			
D. Conceptual teaching strategies			
D1. What effective teaching strategies would you use to teach this big idea? D2. What questions would you consider important to ask in your teaching strategy?			
E. Representations			
E1. What representations would you use in your teaching strategy?			

Fig. 1. CoRe adapted by Rollnick and Mavhunga (2016)

Theoretical Framework

After the initial conceptualisation of PCK, further models emerged in subsequent studies. The most widely cited is that of Magnusson et al. (1999), but may others abound. The commonalities and differences in these models are striking, leading to a quest for convergence in the thinking about PCK. Two PCK summits were held in 2012 and 2016 and the refined consensus model (RCM) (Carlson and Daehler 2019) was the most recent outcome. The RCM model constitutes an important foundation for the framework of this study in terms of the three 'realms of PCK' namely collective PCK (cPCK), personal PCK (pPCK) and enacted PCK (ePCK) (Fig. 2).

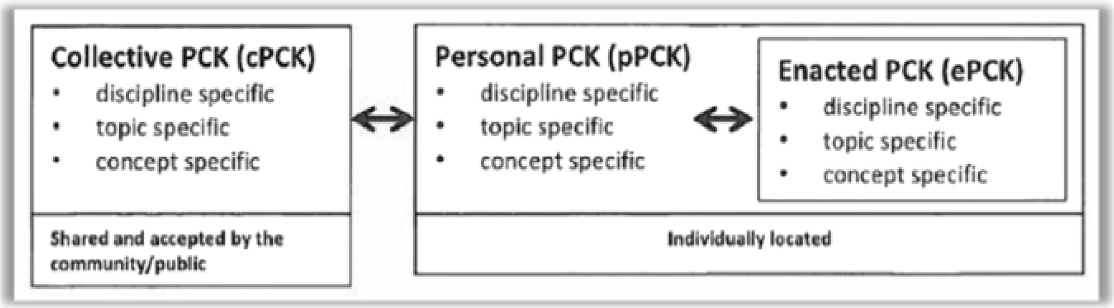


Fig. 2. The multi-dimensional nature of PCK in the Refined Consensus Model (Mavhunga 2019)

Collective PCK (cPCK) is described by Carlson and Daehler (2019, p88) as 'a specialised knowledge base for science teaching that has been articulated and is shared among a group of professionals'. Therefore, cPCK is regarded as agreed knowledge, which is not static but continuously growing through professional interaction. Researchers believe that cPCK is shared through interventions such as teacher training and workshops. The intention is that the improvement of PCK though training should gravitate to pPCK and ePCK of the participants. In the RCM, the teacher's pPCK is considered a 'reservoir of knowledge and skills that the teacher can draw upon during the practice of teaching' (Carlson and Daehler 2019).

Baxter and Lederman (1999) emphasise the importance of translating PCK into action which relates to ePCK in the RCM. They remark that many researchers were of the opinion that teachers' actions are better representations of their knowledge than self-reported displays of their PCK. This finding is in line with the RCM, which places ePCK as a subset of pPCK, acknowledging that the enactment of a teacher's knowledge and skills depends on the specific context in which it is utilised (Carlson and Daehler 2019). Figure 2 illustrates the multidimensional nature of PCK in the RCM (Mavhunga 2019) showing how topic-specific PCK (and each of the other 'grain sizes') is embedded in the three realms of PCK, where grain size refers to the discipline-specifc, topic-specific and concept-specific levels of PCK.

In this study, cPCK was presented to the pre-service teachers during their training with the intention to contribute and shape the pPCK of the individual. The pPCK was accessed by means of CoRes. During teaching practice, the pPCK of pre-service teachers informs their ePCK in teaching situations, which was captured during observations and interviews. In turn, according to the RCM, the teaching experience again shapes the pPCK of the pre-service teacher. The five components of topic-specific PCK (Mavhunga and Rollnick 2013), related to the teaching of electromagnetism, served as the lens through which the ePCK of the pre-service teachers was investigated.

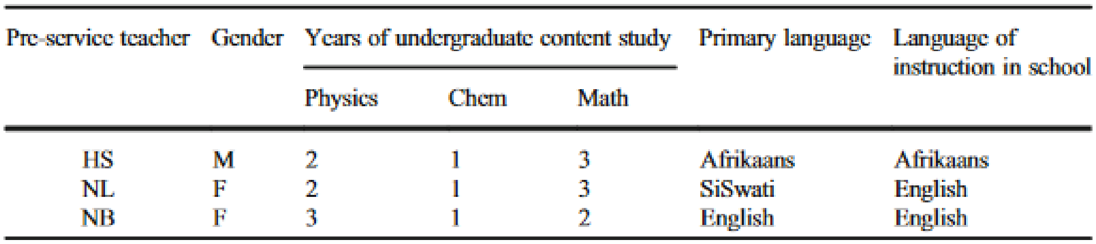
Methodology

This was a case study of physical science pre-service teachers in their final year of study. The concern of case study research is to understand the case being studied and to extend and generalise a theory (Cohen et al. 2013). To achieve this, one should take the suggestion of Gall et al. (1996) into consideration that a case study should be designed in such a way that the findings can be applied to other cases typical of the phenomenon. Then, by building up sufficient case studies, an argument towards generalization can eventually be constructed. The current study can indeed contribute in this manner, because the case we investigated—the PCK of pre-service science teachers in the South African context—is typical of other studies (Kaya 2009; Nilsson 2008; Van Driel et al. 2002).

In the first semester, the pre-service teachers attended a physical science teaching methodology course during which components of PCK, as applied to the topic of electromagnetism, were taught explicitly, regarded here as the training (described more fully below). The class that took part in the training comprised 14 pre-service teachers. Each individual in this group completed a CoRe after the training.

In the second semester, 3 months after the training, all participating pre-service teachers underwent formal teaching experience in schools. From the initial group of 14, a sample of three pre-service teachers was selected purposefully and conveniently. These three were allocated grade 11 classes where they could teach electromagnetism, as scheduled in the curriculum document. They agreed, by signing consent letters, to be interviewed and video-recorded while teaching electromagnetism. They were regarded as representative of the larger group, since they all participated in the training, completed a post-training CoRe and were diverse in terms of gender, race, first language and language of instruction. Table 1 introduces the three participants.

Table 1. Profile of participating pre-service teachers



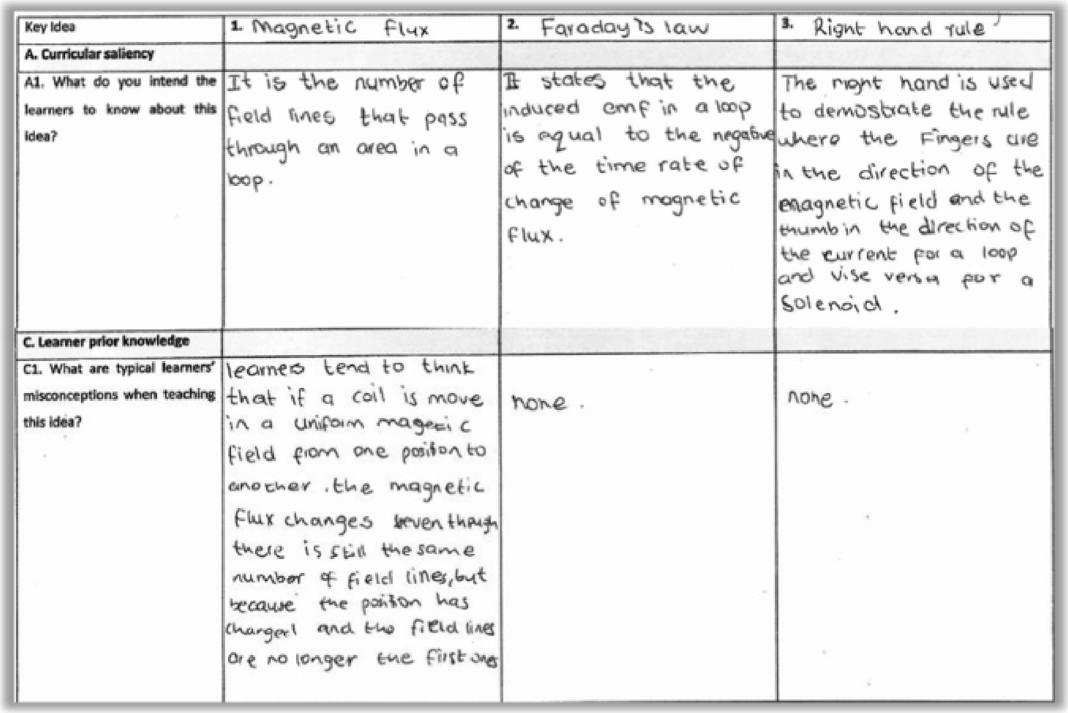
Pre-service teacher	Gender	Years of undergraduate content study			Primary language	Language of instruction in school
		Physics	Chem	Math		
HS	M	2	1	3	Afrikaans	Afrikaans
NL	F	2	1	3	SiSwati	English
NB	F	3	1	2	English	English

At least 60 min of teaching electromagnetism were observed and video-recorded for each participant. After teaching the complete prescribed electromagnetism curriculum, the pre-service teachers participated in a two-part interview, comprising a semi-structured interview, prompting them to reflect on their teaching and a video-stimulated recall (VSR) interview during which they viewed sections of their lessons and were prompted by the researchers to reflect and comment on their actions and decisions.

The Training

The five components of topic-specific PCK as described above in the framework for the study were addressed during the training using appropriate sub-topics in magnetism and electromagnetism. The way the five components, separately and combined, support the transformation of CK for teaching, was communicated. Appendix B, an outline of the structure of the training, shows how the topic of electromagnetism was employed to instruct participants about topic-specific PCK components.

Baxter and Lederman (1999) summarised the salient aspects of teachers' PCK obtainable through research as: what teachers know, what they do and why they do it. In this study, 'what the pre-service teachers know' (pPCK) immediately after the training but before teaching the topic was revealed through a comprehensive paper-and-pencil task in the form of an adapted content representation (CoRe) (Rollnick and Mavhunga 2016) on the teaching of electromagnetism. When constructing the CoRes, we asked the pre-service teachers to select key ideas from grade 11 electromagnetism and present them in a proposed teaching sequence. Following this, they applied their knowledge about teaching the key ideas by responding to the prompts in the CoRe-tool, for example: What do you intend the learners to know about this idea? What concepts need to be taught before teaching this idea? What are typical learners' misconceptions? (see Fig. 3).



Key idea	1. Magnetic flux	2. Faraday's law	3. Right hand rule
A. Curricular saliency			
A1. What do you intend the learners to know about this idea?	It is the number of field lines that pass through an area in a loop.	It states that the induced emf in a loop is aqual to the negative of the time rate of change of magnetic flux.	The right hand is used to demostrate the rule where the Fingers are in the direction of the magnetic field and the thumb in the direction of the current for a loop and vise versa for a Solenoid.
C. Learner prior knowledge			
C1. What are typical learners' misconceptions when teaching this idea?	learners tend to think that if a coil is move in a uniform magecic field from one position to another. the magnetic flux changes even though there is still the same number of field lines, but because the position has changed and the field lines are no longer the first ones	none.	none.

Fig. 3. Exemplar sections from a pre-service teacher's CoRe

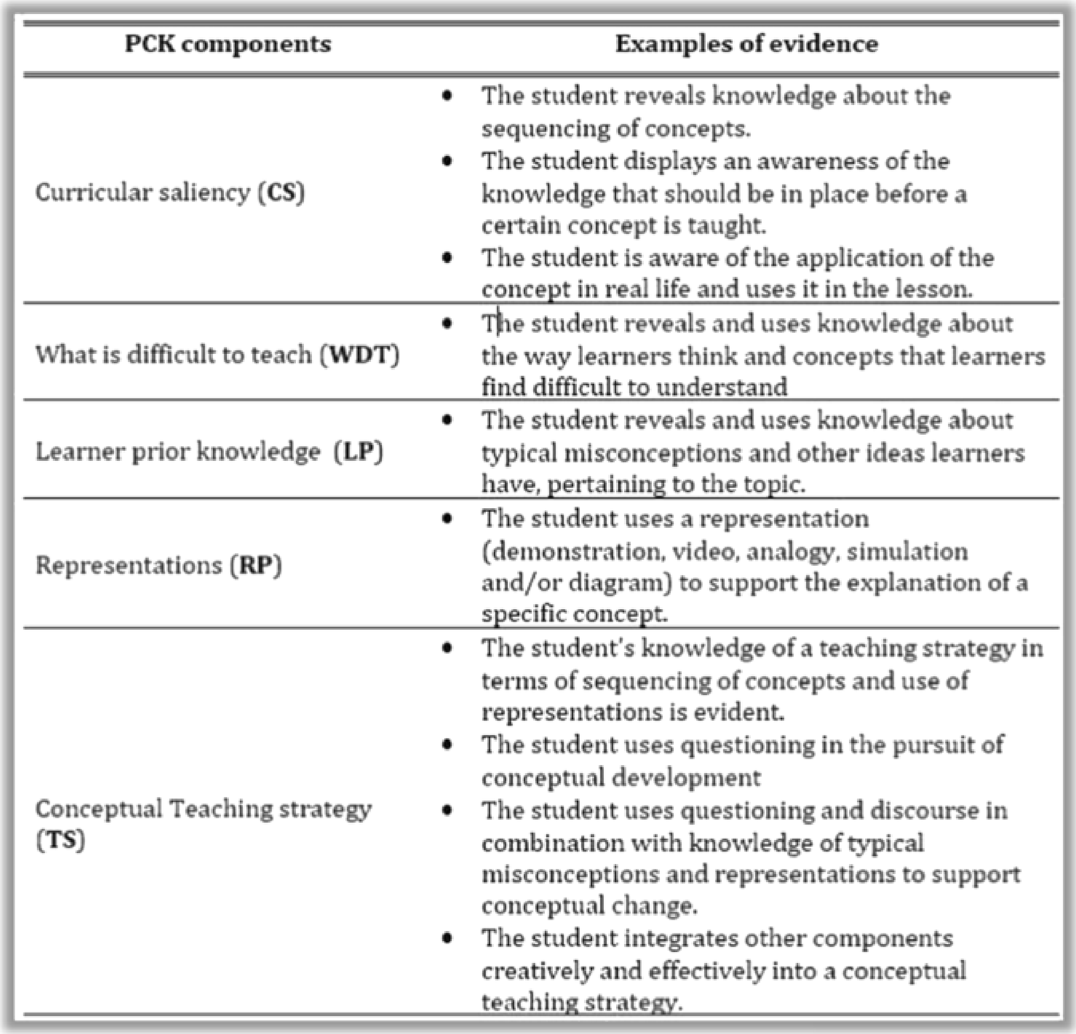
Analysis of the Data

During analysis of the lessons and interviews, we searched for evidence of manifestations and interaction of the PCK components as taught during the training as both yield evidence of quality of PCK about the topic (Mavhunga and Rollnick 2017; Park and Chen 2012). The interviews also afforded the opportunity to elicit pre-service teachers' pedagogical reasoning not possible through lesson observation only (Chan et al. 2019). The following analysis process was followed:

- The CoRes constructed by the pre-service teachers after the training were analysed and later compared with what transpired during the lessons. When obvious discrepancies occurred, we required participants to reflect about that in the interview. We report about such occurrences in the 'Findings' section.
- We watched the video recordings at least twice for a lesson overview.
- We wrote a narrative account of each lesson which was divided into chronological teaching sections of about 3 to 12 min each, which typically entailed one of the following:
- assessment of knowledge already in place;
- the teaching of a new concept;
- consolidation of concepts recently taught;
- discussion of class or homework exercises.
- For each section, we identified teaching events which were analysed for evidence of enactment of one or more of the topic-specific PCK components (Fig. 4).
- The teaching events were rated using a rubric for enacted PCK (Appendix A) and levels, restricted, adequate or rich, representing the quality of the enactment, were assigned for each component by one of the researchers. Possible researcher bias

(such as the Hawthorne and the halo-effects) was countered by rigidly adhering to the category descriptions in the rubric. Validation took place through independent scoring of the identified teaching events by the second and third authors who were expert science teacher educators and understood both languages of instruction. Where differences occurred, scores were discussed by all three authors and adjusted until agreement had been reached and the rubric was refined where necessary. Final scoring took place after refinement of the rubric.

- For the VSR interview, we selected three or four sections from each pre-service teacher's lessons that revealed interesting aspects of their teaching related to key ideas selected in their CoRes. Time restrictions did not allow for more. The components listed in Fig. 4 were used to code the comments made during the VSR interview; for example, if a pre-service teacher reflected on the use of a representation in the first event of section one of a lesson that comment was coded as '[Interview (RP)]'.



PCK components	Examples of evidence
Curricular saliency (**CS**)	• The student reveals knowledge about the sequencing of concepts. • The student displays an awareness of the knowledge that should be in place before a certain concept is taught. • The student is aware of the application of the concept in real life and uses it in the lesson.
What is difficult to teach (**WDT**)	• The student reveals and uses knowledge about the way learners think and concepts that learners find difficult to understand
Learner prior knowledge (**LP**)	• The student reveals and uses knowledge about typical misconceptions and other ideas learners have, pertaining to the topic.
Representations (**RP**)	• The student uses a representation (demonstration, video, analogy, simulation and/or diagram) to support the explanation of a specific concept.
Conceptual Teaching strategy (**TS**)	• The student's knowledge of a teaching strategy in terms of sequencing of concepts and use of representations is evident. • The student uses questioning in the pursuit of conceptual development • The student uses questioning and discourse in combination with knowledge of typical misconceptions and representations to support conceptual change. • The student integrates other components creatively and effectively into a conceptual teaching strategy.

Fig. 4. Exemplary evidence of enactment of PCK components

- The knowledge of the topic-specific PCK components revealed by the participants in their CoRes, their enactment of these components during teaching and their

> pedagogical reasoning during the interviews was considered and compared, to establish how and when the pre-service teachers integrate their training into their personal and enacted PCK about the teaching of electromagnetism.

Findings

All three participants were observed teaching the first idea, being the magnetic field associated with current-carrying wire. Due to logistical constraints however, only HS and NL were observed teaching Faraday's law and the related concept of magnetic flux. NB's approach to this sub-topic and how this transpired in her teaching were deduced from her CoRes and interview.

The findings are presented in terms of the five components through which the ePCK of the teachers was investigated as they relate to the two main curriculum ideas in electromagnetism.

First Main Idea: Magnetic Field Associated with Current-Carrying Wire

Curricular Saliency

The national curriculum document (Department of Basic Education 2011) suggested the following sequence (p.86): provide evidence for the magnetic field around a current-carrying wire, apply the right-hand-rule to a straight wire, a single wire-loop and a solenoid and then draw the magnetic fields for these three cases. All three participants followed this suggested sequence.

NB started her lesson by making sure that learners understood that the existence of magnetic fields could be established with the use of iron filings or compasses. The purpose was that learners could appreciate the behaviour of the compasses or iron filings around a current-carrying conductor. She did not tell them beforehand that a magnetic field exists around a current-carrying wire, but presented the video simulation and let the learners observe the deflection of the compasses and the behaviour of iron filings. Furthermore, she drew learners' attention to the fact that the magnetic field gets weaker as the distance from the conductor increases, even though understanding of this idea would only become essential when teaching the change in magnetic flux.

NB's pedagogical reasoning during the VSR interview about this section of her lesson indicated that she was satisfied with her sequencing of the sub-ordinate ideas:

> *NB: I think it would have,…watching it now, I could not keep up with myself. So, I think that I just moved too fast…. But in terms of the sequencing, especially in this part, I'd just kept it the same*. [Interview (CS)].

Comparison with the category descriptions in the rubric (Appendix A) indicates that NB's knowledge of curricular saliency can be rated rich.

Similar to the first participant NB, both NL and HS showed understanding of the sequencing of concepts in the curriculum by building on knowledge already in place to develop new ideas. They verified learners' understanding of the behaviour of compasses in a magnetic field and affirmed that learners realised that compasses could be used to indicate the existence of a magnetic field. When moving on to explaining the field around a current-carrying loop, they realised the importance of explaining the direction of the field in the centre of the loop, since the field of a solenoid builds on this idea. In this section, their knowledge of curricular saliency was evident in the way they sequenced and scaffolded the concepts and both were scored rich.

What Is Difficult to Teach

This component was not displayed during the teaching of this particular main idea. In their CoRes, written after the training, none of the participants indicated that they foresee difficulties in teaching this idea and neither did they mention difficulties experienced with this idea in their interviews. During the lessons, it was observed that the learners did not have problems understanding the concept.

Learner Prior Knowledge

All three participants noticed learners' tendency to disregard the importance of using the right hand when predicting the direction of the magnetic field, given the direction of the current in the wire. It is possible that they remembered the issue from their school days, as evidenced by NB:

> *…but I thought it was important because from my own experience, it was stuff that I did not really know, or stuff that I skipped,… 'cause a lot of the stuff, when I'm teaching, I reflect on how I was taught it, and how I can make improvements."* [Reflection NB]

In Fig. 5, NL shows how using the left hand and the right hand will lead to the opposite predictions of the magnetic field direction.

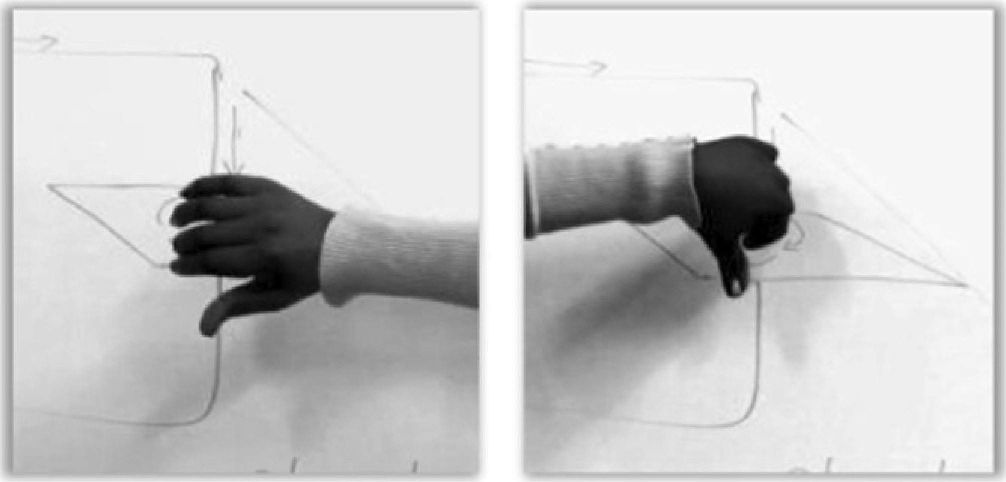
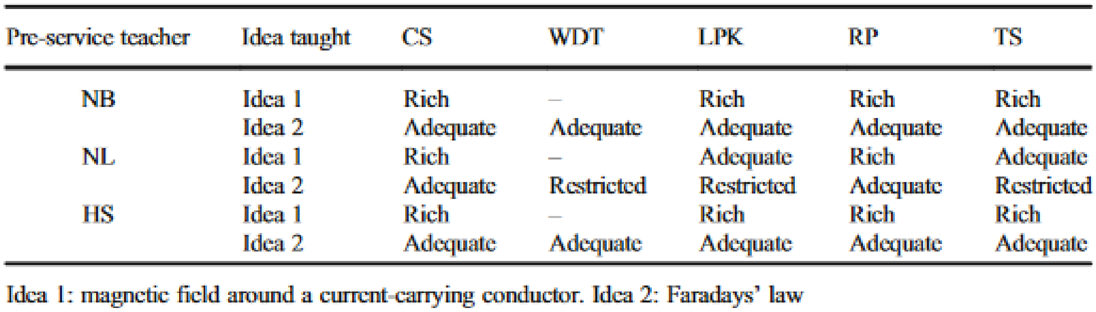


Fig. 5. Student NL explaining the difference between using the right and left hands

NL displayed awareness of learners’ prior knowledge in their confusion of electric charges and magnetic poles. She asked: ‘Where do you find a magnetic field’? and a learner replied, ‘Around a charge’. She responded: ‘Don’t confuse magnetism with charges’, but then, she added that magnetism has nothing to do with charge, revealing her own poor conceptual link between magnetism and moving charges. Later, she asked: ‘What does a compass do when it is in a magnetic field’? and a learner responded: ‘It points towards the positive of the magnetic field’ to which NL replied: ‘Remember with magnets we don’t have positive and negative poles’. Displaying awareness of learners’ thinking combined with her ignorance of the role of moving charge in magnetism resulted in a score of adequate in enacted PCK about learners’ prior knowledge (see Table 2).

Table 2. Summary of the participants’ scores for the different topic-specific PCK components



Pre-service teacher	Idea taught	CS	WDT	LPK	RP	TS
NB	Idea 1	Rich	–	Rich	Rich	Rich
	Idea 2	Adequate	Adequate	Adequate	Adequate	Adequate
NL	Idea 1	Rich	–	Adequate	Rich	Adequate
	Idea 2	Adequate	Restricted	Restricted	Adequate	Restricted
HS	Idea 1	Rich	–	Rich	Rich	Rich
	Idea 2	Adequate	Adequate	Adequate	Adequate	Adequate

Idea 1: magnetic field around a current-carrying conductor. Idea 2: Faradays’ law

Representations

Although the national curriculum document (Department of Basic Education 2011) only prescribed giving evidence of a magnetic field around a straight wire, all three pre-service teachers also used representations for the magnetic field around a solenoid. Two of the participants incorporated demonstrations as representations in their teaching similar to demonstrations presented during the training. NB on the other hand did not use practical demonstrations but relied on videos and computer simulations and only presented equipment as examples. When asked about her preference for using virtual evidence rather than demonstrations, she cited the lack of equipment as a reason:

> *NB: And then, also there was also quite a nice, … one of the solenoids…, but it had like been broken, and everything. And I was also just a bit intimidated by the equipment, so I thought, let me just go for the simulations.* [Interview (RP)].

Evidence of rich application of knowledge about representations was displayed when all three participants combined different representations, such as a demonstration or a video supported by a corresponding diagram. Figures 6 and 7 show typical examples presented by NB and HS.

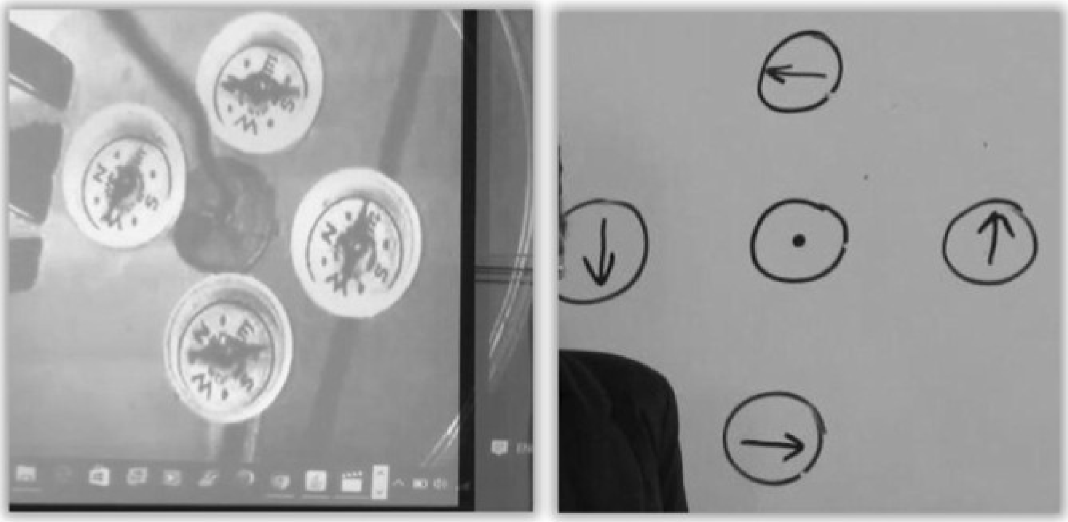


Fig. 6. Representations by NB for the magnetic field around a straight wire

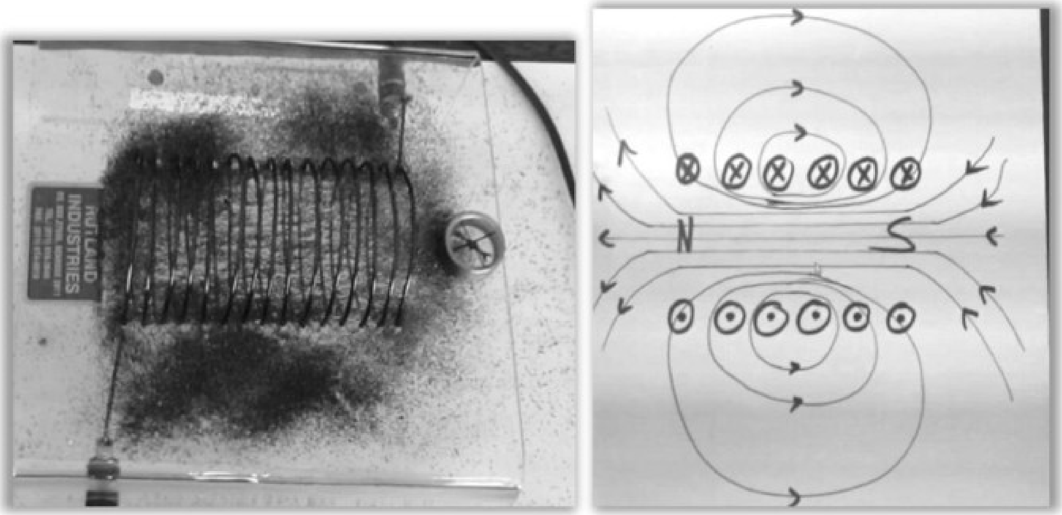


Fig. 7. Representations by HS for the magnetic field around a solenoid

Conceptual Teaching Strategies

In teaching this key idea, the participants used effective sequencing of teaching events i.e. first the straight wire, followed by a wire loop and then the magnetic field of a solenoid. They integrated their understanding of the curriculum and representations effectively. Since this component relies on the integration and interaction of the other components, NL was scored adequate as a result of her inability to address learners' conceptual link between electric charge and magnetism.

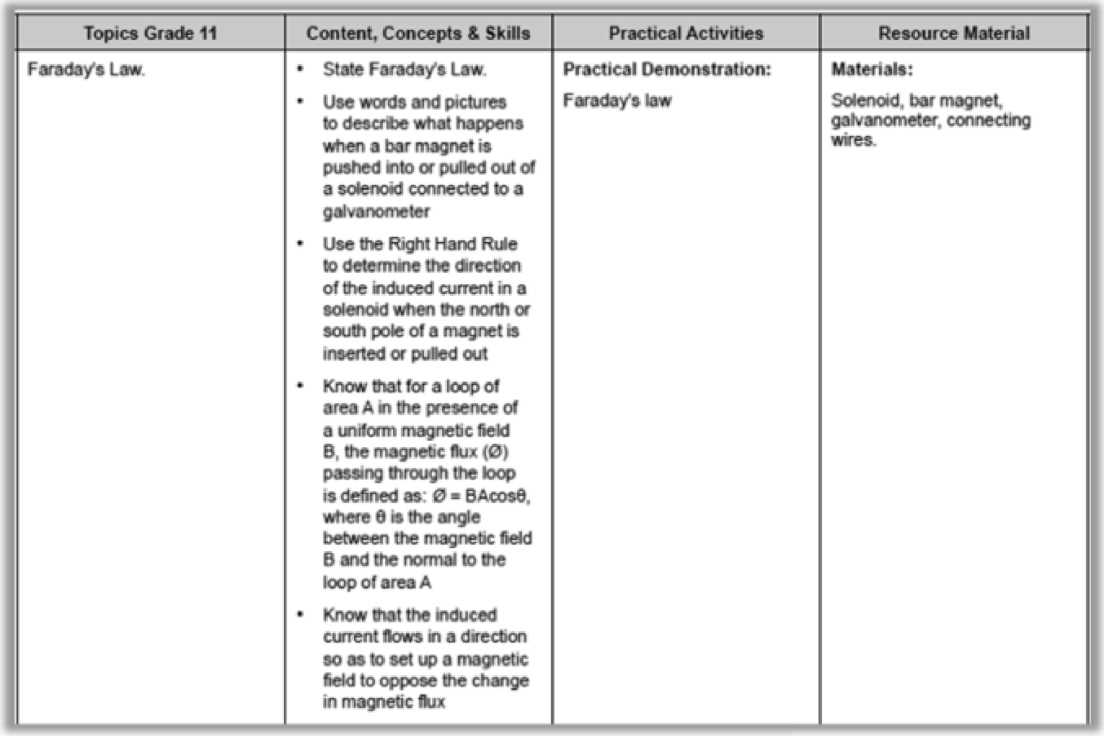
NB and HS were scored rich for this component. The ease with which they translated the content into understandable units, their ability to listen attentively to learners' responses and address incorrect thinking culminated in good conceptual teaching strategies.

However, a different dynamic prevailed when the participants taught the second topic in the curriculum, namely Faraday's law.

Second Main Idea: Faraday's Law

Curricular Saliency

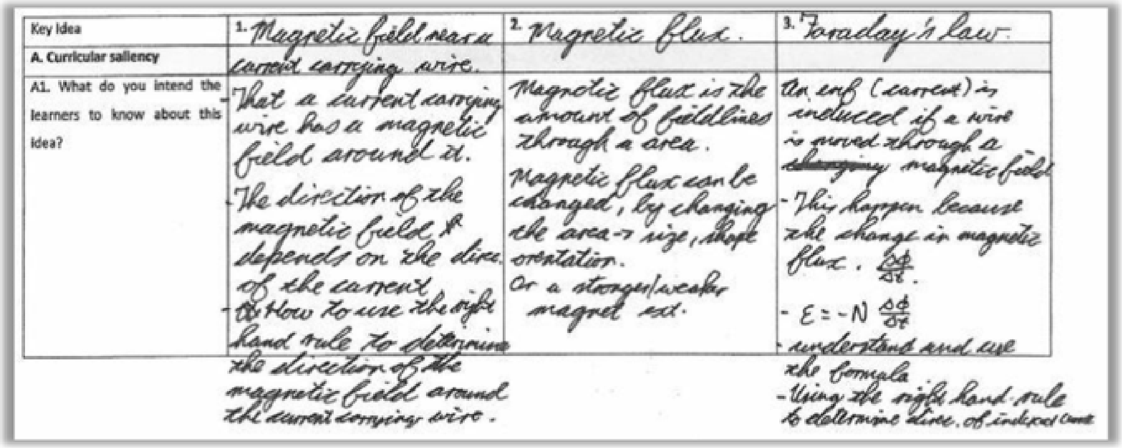
Figure 8 shows the presentation of Faraday's Law in the national curriculum document (Department of Basic Education 2011). The document starts with 'State Faraday's law', which in fact requires knowledge about the concept of magnetic flux, which only follows later in the suggested sequencing.



Topics Grade 11	Content, Concepts & Skills	Practical Activities	Resource Material
Faraday's Law.	• State Faraday's Law. • Use words and pictures to describe what happens when a bar magnet is pushed into or pulled out of a solenoid connected to a galvanometer • Use the Right Hand Rule to determine the direction of the induced current in a solenoid when the north or south pole of a magnet is inserted or pulled out • Know that for a loop of area A in the presence of a uniform magnetic field B, the magnetic flux (Ø) passing through the loop is defined as: $\text{Ø} = BA\cos\theta$, where θ is the angle between the magnetic field B and the normal to the loop of area A • Know that the induced current flows in a direction so as to set up a magnetic field to oppose the change in magnetic flux	**Practical Demonstration:** Faraday's law	**Materials:** Solenoid, bar magnet, galvanometer, connecting wires.

Fig. 8. Extract from the curriculum document: grade 11 electromagnetism (Department of Basic Education 2011)

During the training, strong arguments were presented to the pre-service teachers for teaching magnetic flux before attempting to teach the equation representing Faraday's law. All three participants wrote CoRes suggesting that they will teach magnetic flux as a separate key idea before teaching Faraday's law. In the CoRes, the key ideas were listed in the sequence they planned to teach; (see Fig. 9), yet 3 months later, when they actually had to teach it, they resorted to the sequence suggested in the curriculum document.



Key Idea	1. Magnetic field near a current carrying wire.	2. Magnetic flux.	3. Faraday's law.
A. Curricular saliency			
A1. What do you intend the learners to know about this idea?	- That a current carrying wire has a magnetic field around it. - The direction of the magnetic field & depends on the direc. of the current - How to use the right hand rule to determine the direction of the magnetic field around the current carrying wire.	Magnetic flux is the amount of fieldlines through a area. Magnetic flux can be changed, by changing the area -> size, shape orentation. Or a stronger/weaker magnet ect.	An emf (current) is induced if a wire is moved through a ~~changing~~ magnetic field - This happen because the change in magnetic flux. $\frac{\Delta\phi}{\Delta t}$. - $\mathcal{E} = -N\frac{\Delta\phi}{\Delta t}$ - understand and use the formula - Using the right hand rule to determine direc. of induced curr.

Fig. 9. The planned sequence of HS as revealed in the CoRe

All three started the teaching of the key idea by stating Faraday's law as suggested by the curriculum. They stated Faraday's law in terms of the rate of change in magnetic flux $\left(\frac{\Delta\phi}{\Delta t}\right)$, and introduced the formula $\varepsilon = -N\frac{\Delta\phi}{\Delta t}$, only to find out that the learners made no sense of it. Afterwards, in the interviews, their pedagogical reasoning about their decision to teach Faraday's equation and magnetic flux in this particular sequencing was evident, for example:

> *HS: … I thought to do Faraday's law first and show it practically, and then do magnetic flux to explain why Faraday's law works and what happened, and then I would have gone to Lenz's law, but the learners did not understand the magnetic flux well after Faraday's law. It confused them a bit … So for the next period I presented the lesson again and changed it, … first to finish magnetic flux and then proceed to Faraday's law*. [Interview: CS].

Revealing knowledge of curricular saliency, NB reflected on the sequencing of concepts such as magnetic flux and induced current and considered changing the sequencing when teaching it again:

> *NB: Although, I was thinking that maybe, it would've helped, to teach magnetic flux right at, not right at the beginning, but before actually doing the magnetic-field-induces-current thing. But I did not do that, though.* [Interview: CS]

Although all the participants taught the ideas in an ineffective sequence, they all realised afterwards that a change in the sequence would be fruitful. As a result, the three participants were scored adequate for enacting the component of curricular saliency.

What Is Difficult to Teach

Apart from struggling to establish a proper sequence to present these concepts, they found this sub-topic difficult to teach as seen in the following remark:

> *NB: I found magnetic flux quite difficult. I think out of everything, even the Lenz's law stuff. That was something I actually only understood for the first time this year, the whole … I do not know why but I found it quite difficult.* [Interview: WDT]

She felt about the idea of magnetic flux: '*as though it were some obstacle in between what we had done and Faraday's law*'. She remarked that:

> '*I decided to let the learners do… when they were able to actually do it themselves on paper, and I could see, okay, they understand it*' [Interview: WDT]

Even though she did not manage to break down the idea into understandable units, she realised the need to change her approach and was scored adequate.

In her lesson about magnetic flux, it was however evident that NL was not in command of the content and struggled to teach this idea. She did not approach the topic conceptually and relied on the repetition of the definition and the application of the equation. This topic was difficult for her to teach and she did not have a strategy to approach it, displaying restricted knowledge of this component.

HS admitted during the interview that teaching magnetic flux and Faraday's law was not easy. He said the learners found these concepts very abstract mostly because magnetic field lines cannot be seen. He used a self-constructed model (discussed under the 'Representations' section) to support the teaching of these ideas, but still failed to clarify some of the aspects from which common misconceptions arise. These misconceptions include the belief that only the magnet should be moved when current is induced and that current will be induced even if the magnet is stationary inside the solenoid. His enactment of this component was score adequate.

Learner Prior Knowledge

While teaching Faraday's law, NB realised that learners confused the mere presence of magnetic field lines with the change in magnetic flux. She remarked:

> *NB: Calculating magnetic flux itself, understanding that it's the field lines through a certain area, that I think is fine. I think it's when you have a change in magnetic flux. That's where the problem comes in. How is that change brought about*? [Interview LP].

NB identified the misconception but did not suggest any ideas to address it. As such, her knowledge of this component was scored adequate.

In the lesson about magnetic flux, NL worked through a problem that required the calculation of the amount of flux through a square loop that she had drawn on the board. After completing the calculation, she asked learners to predict the direction of the 'induced' current even though the problem did not refer to changing magnetic flux. She herself possibly held the misconception that all magnetic field lines 'move' as suggested by her use of the misleading phrase: 'The magnetic field *flows* from north to south'—creating the impression of changing magnetic flux. She proceeded to draw the direction of the 'induced current’ on the diagram, according to the right hand rule for a current carrying loop (Fig. 10). Inducing a misconception while teaching resulted in NL to be scored restricted for this component.

Fig. 10. NL’s drawing that revealed her own misunderstanding

Although HS used a self-constructed model (discussed under the ‘Representations’ section) (Fig. 10) to support the teaching of induced current, he still failed to clarify some of the aspects from which common misconceptions arise as discussed earlier. In his explanation, he said, ‘the magnetic field lines *cut* through the loop’ without mentioning the change in flux. A learner asked: ‘Why does nothing happen when the magnet is kept still in the solenoid since there are still field lines cutting through the loop’? The learner’s question implied an impression that the magnetic field lines ‘cutting’ through the surface was the requirement for induced current. It was only then that HS mentioned the need for the magnetic flux to change for current to be induced, but in his self-constructed model, the learners could not perceive the changing magnetic flux. It was evident that HS's knowledge of this component was still developing and as a result, his enactment was rated adequate.

Representations

Although we did not observe NB teaching Faraday's law, we can conclude from remarks in her interview that her teaching of the idea was not very successful:

> *I found it a bit difficult, to explain to the learners, magnetic flux, after having shown them a moving magnet. I do not know why, but it just did not seem to tie together. It seemed like I was teaching a completely different concept. It moved away from what they had seen to some theoretical, something abstract somewhere.* [Interview: RP]

We concluded that her use of a representation (a moving magnet) did not result in conceptual development, and according to the rubric (Appendix A), her competence in using representations to teach this idea should be scored adequate.

To teach Faraday's law, NL selected representations that did not support the development of the concept of magnetic flux. She was under the impression that magnetic flux could only be explained in terms of a uniform magnetic field 'straight lines' and presented that as a reason for not using a simulation as a representation:

> *But in the whole magnetic flux concept you are looking at a part where the magnetic field lines are straight. And then I think, same with simulations, it's more of an ideal situation, and it is one of the reasons I did not do the simulation for this. I prefer to draw it, but … it's the fact that the lines are not straight.* [Interview: RP]

Although the discussion during the training did not exclude curved magnetic field lines in the explanation of magnetic flux, NL's perception did not change as a result of the training. This perception contributed to the fact that NL found magnetic flux difficult to teach. For this section, her knowledge of the use of representations to translate the content into understandable units was scored adequate.

When HS realised that learners were confused by the references to magnetic flux and change in magnetic flux, he designed a piece of equipment to support his explanation, which he used when he retaught the idea. He used two laser beams as an analogy to magnetic field lines and a transparency with black lines to represent the turns of a solenoid (Fig. 11). By moving the transparency up and down through the slot in the cardboard box, he attempted to make the interaction of the field lines and the wire-loops visible.

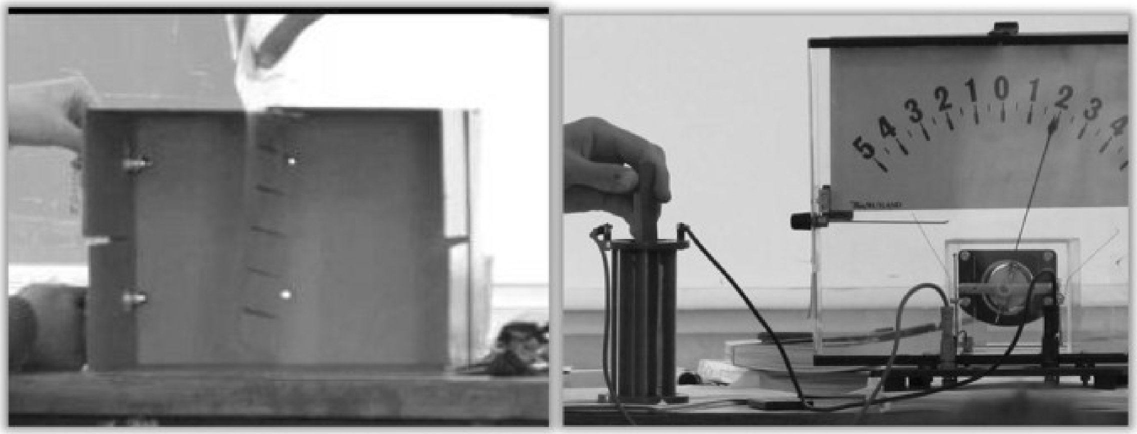


Fig. 11. The self-constructed model combined with a demonstration used by HS

A more successful application of this model was the use of a plastic loop to show how rotation of the loop, often described in textbook problems, changes the magnetic flux (Fig. 12). He used this to explain the orientation of the surface to the magnetic field, as described in the equation φ = BAcosθ.

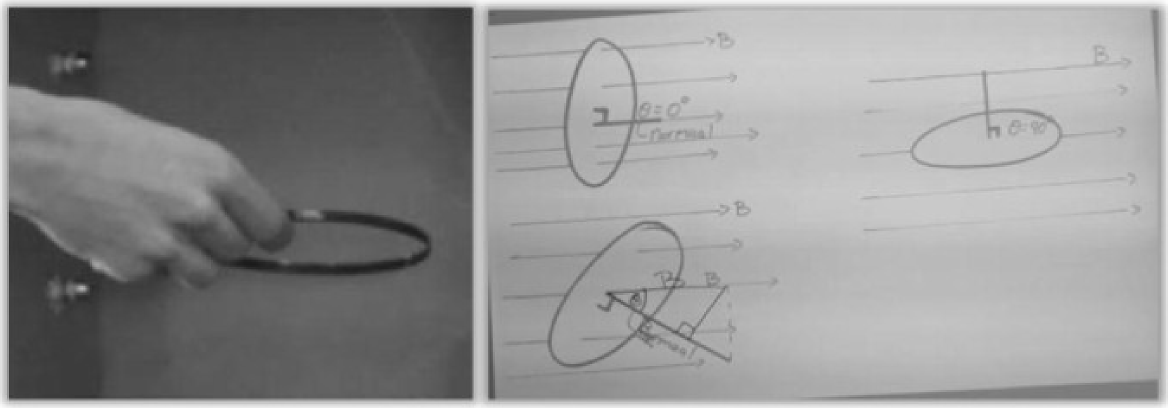


Fig. 12. Representation used by student HS

It was evident that HS made extensive use of demonstrations in combination with diagrams to support conceptual understanding. However, when he was unsure of the concepts underpinning the key idea, he did not use the representations to their full potential and conceptual development was limited. As such, his knowledge of this component in the second lesson was scored adequate.

Conceptual Teaching Strategies

Rating this component relies heavily on evidence that the other components were integrated into an effective conceptual teaching strategy. Since NB was not observed teaching Faraday's law, we could not make a conclusive judgement about her competence regarding this component. However, by her own judgement in the interview, she enacted none of the other components effectively. As a result, we deduced that her conceptual teaching strategies could not have been enacted at a level higher than adequate.

NL wrote in her CoRe that magnetic flux is not difficult to teach since all the information needed is available in the equation. When teaching magnetic flux for the first time, it was observed that NL regarded the teaching of this key idea as mere application of an equation and became aware of the difficulties of understanding the concept only after she attempted to teach this concept. Her lack of thorough understanding of the concepts proved to be detrimental to the effective teaching of these ideas and consequently her knowledge of this component was scored restricted.

In the interview, HS expressed his beliefs about the role of the teacher in the classroom:

> *HS: [It] is not just transferring the knowledge to learners, but to lead them a bit more and let them see why things happen rather than just telling them … and by practically pointing out to them and explaining to them why some things happen, or why not.*

It seems as if HS made an honest attempt to follow this intention. Through questioning and discussion, he was able to integrate his knowledge of learners' ideas and representations effectively. When comfortable with the content, he asked questions to elicit learners' knowledge, waited for answers and used the answers to support further development of ideas. However, his intention did not materialise during his teaching of Faraday's law when he reverted to procedural teaching especially when conducting demonstrations. This may be symptomatic of a lack of confidence with the content of the second key idea. His discourse during practical demonstrations amounted to a 'running commentary' and a tendency to interpret observations for the learners. He asked fewer questions initiating critical thinking, preferring to lecture the content. HS's competence in conceptual teaching strategies was as a result, rated adequate.

Discussion and Implications

Table 2 shows a summary of levels assigned using the rubric for ePCK about electromagnetism (Appendix A) as discussed in the previous section. The five components listed in figure are the headings of the last five columns as explained in Fig. 4.

During her lesson presentations and reflection about her practice, NB provided evidence that she had a rich knowledge of the topic-specific PCK components in electromagnetism and the ability to enact this knowledge noticeably in a teaching situation. However, she was not observed teaching Faraday's law. Since she remarked that she found this sub-topic difficult to teach and that the sequencing in which she presented it was ineffective, it can be inferred that her ePCK in this topic may not have been rich. Nevertheless, she displayed the ability to reason pedagogically about and reflect critically on her actions and decisions and was aware of potential changes and adaptations to improve her teaching.

It was evident in both HS and NL's teaching of the first key idea that they were capable of rich enactment of PCK. On the other hand, when they were not in command of the content, they resorted to procedural teaching and did not venture beyond the minimum requirements described in the curriculum document and textbooks.

The demand on a teacher's CK is high and lack of CK has a negative impact on the quality of teaching (Rollnick et al. 2008). Furthermore, lack of knowledge of content and the curriculum may affect the pre-service teachers' ability to identify major concepts and affect their decisions about how much time to spend teaching specific ideas (Friedrichsen et al. 2009). This was evident both in a remark of NB that she wasted time in revising pre-concepts too thoroughly at the expense of more important ideas and when NL repeated the definition of magnetic flux over and over again.

Apparently, these pre-service teachers needed to experience the problems arising from teaching Faraday's equation before magnetic flux, before they realised the advantage of the sequence proposed during the training. Their self-proclaimed lack of confidence in their CK about electromagnetism might have resulted in their reluctance to venture off the sequence suggested in the curriculum document. Findings suggest that for these three pre-service teachers, knowledge about what is difficult to teach and learner prior knowledge and misconceptions was not gained from the training as much as from their formal experience of teaching the topic or possibly that they realised the relevance of what was taught during the training when they had to teach the topic themselves. This may also suggest that actual teaching of the topic resulted in enhanced CK.

Remarks made by all three pre-service teachers alluded to the fact that their own experiences as learners had an influence on the way they taught science and the instructional strategies they employed, which concurs with findings by Friedrichsen et al. (2009). This also resonates with the question posed by Grossman (1991): 'How can these deeply ingrained lessons from the apprenticeship of observation be challenged'? Evidence from the three pre-service teachers in this part of the study suggests that the challenge is indeed greater when the pre-service teacher is not in command of the content.

Even though these pre-service teachers had been exposed to micro-lessons teaching to peers during the training, it is impossible to know how they would have taught the topic in an actual classroom situation without being exposed to the training (a limitation of the study), yet it was possible to see implementation of the topic-specific PCK components, although at different levels. Furthermore, the interview excerpts above suggest that these components developed during their teaching of the topic. Conceptual teaching strategies were enacted at varying levels depending on the role the other components played in a specific teaching event, and on the CK of the pre-service teacher. In some cases, such as teaching the magnetic field around a solenoid, the pre-service teachers used very similar sequencing and representations, but the ways in which they incorporated these were not equally rich. These differences in the enactment of conceptual teaching strategies could be attributed to the type of questions and discussions used to transform the content for learners' comprehension. Rich enactment and proper interaction of the components of topic-specific PCK seemed to be difficult to accomplish when the participants felt intimidated by or did not have a sound conceptual understanding of the concepts.

Another finding, related to 'science language' emerged during the data analysis, which may be a consequence of teaching the topic for the first time. Pre-service teachers sometimes use language that casts doubt on their own understanding of the content and if used in teaching may lead to incorrect understanding by the learners. They also inadvertently confused themselves and their learners by using inappropriate words to describe a magnetic field. In constructing the CoRe, one pre-service teacher wrote: ‘the magnetic field is *going* from north to south’ and both NL and HS used phrases in their lessons such as ‘the magnetic field lines flow or move from north to south’, suggesting that the magnetic field moves. This could engender learner thinking that the magnetic field itself can ‘go somewhere,’ which has serious implications for understanding the change in magnetic flux. The pre-service teachers’ explanation of induction of current by moving a magnet in and out of a solenoid focussed on the motion of the magnet rather than the importance of the change in magnetic flux, leading to the notion that the motion necessary to induce current is in fact the motion or flow of the magnetic field. These misunderstandings resulting from poor verbalisation probably contributed to the belief that magnetic flux and Faraday’s law were difficult concepts to teach. Realization that the use of language in teaching electromagnetic concepts may hinder the transformation of content into understandable units may point to an area for new research.

The results of the study should not be generalised to the broad population of pre-service physical science teachers. The study was conducted with pre-service teachers that were diverse in terms of gender, race and primary language, but they were all studying in the Faculty of Education of the same university. The study does, however, complement the work of researchers such as Abell et al. (2009), Kind (2009) and Gess-Newsome (2015) and contributes to theory about the development of PCK of pre-service teachers.

Furthermore, considering the nature of the construct topic-specific PCK, it is expected that a teacher’s PCK may not be the same from topic to topic. In addition, it was found in this study that pre-service teachers’ PCK was not even the same over different key ideas in the same topic. As explained in the discussion, it was clear that participants generally revealed a higher level of competence in the key idea magnetic field around a current-carrying conductor than in Faradays’ law. This aspect points to the necessity of taking into consideration the grainsize of the content accessed in a teacher’s PCK (Mavhunga 2019).

Logistical aspects enforced another limitation on this study, aimed at establishing whether pre-service teachers are able to enact learned PCK during teaching. There was no opportunity to obtain an indication of the baseline enacted PCK of the participants. The pre-service teachers did not have access to schools in the first term of the year, and the enacted PCK of the pre-service teachers could not be accessed before the start of the training. Hence, we could not assume that the aspects of their PCK about electromagnetism that became evident during the lesson presentations necessarily resulted from knowledge gained during the training. As such, we could not claim that the enacted knowledge observed during lessons was the result of the training. We merely reported on obvious links and similarities between issues discussed in the training and knowledge revealed during teaching.

Limitations related to observer effects and personal bias, including observational bias, the halo and Hawthorne effects were countered by rigidly adhering to the enacted PCK rubric.

Conclusion

Knowing how pre-service teachers enact the topic-specific PCK components when they teach a topic for the first time may guide teacher educators in the design of method courses to support the development of the PCK in different curriculum topics. Teacher educators should be aware of the fact that pre-service teachers need to be aware of curricular demands and interpretation in terms of the components of topic-specific PCK. Furthermore, it is important for science teacher educators to know that their work with pre-service teachers contributes significantly to their development as teachers. This study suggested that training in terms of course work and experience during teaching practice had a positive influence on the teacher knowledge of the pre-service teachers. Constructing CoRes, teaching the topic and reflecting on their teaching during interviews, all contributed to their experience during teaching practice. Findings indicated that the PCK taught during the training did not gravitate to the pPCK and ePCK of the pre-service teachers in all the components, until after the opportunity to teach the topic and to reflect critically about their teaching.

However, the contribution made by mentor teachers during the internship to the development of pre-service teachers' PCK was not investigated and may leave scope for further research. Furthermore, scope for research lies in establishing the link between the pPCK and ePCK of the teacher and learner outcomes in terms of sound conceptual understanding and performance. This link lies not only in the assumption that better PCK will result in better performance but equally important, in the way in which teachers use learner outcomes to inform their classroom practice and to shape their PCK.

References

Abell, S. K., Rogers, M. A. P., Hanuscin, D. L., Lee, M. H., & Gagnon, M. J. (2009). Preparing the next generation of science teacher educators: a model for developing PCK for teaching science teachers. *Journal of Science Teacher Education, 20*(1), 77–93.

Alonzo, A. C., & Kim, J. (2016). Declarative and dynamic pedagogical content knowledge as elicited through two video-based interview methods. *Journal of Research in Science Teaching, 53*(8), 1259–1286.

Alonzo, A. C., Kobarg, M., & Seidel, T. (2012). Pedagogical content knowledge as reflected in teacher–student interactions: Analysis of two video cases. *Journal of Research in Science Teaching*, 49(10), 1211–1239.

Baxter, J. A., & Lederman, N. G. (1999). Assessment and measurement of pedagogical content knowledge. In *Examining pedagogical content knowledge* (pp. 147–161). London: Kluwer Academic Publishers.

Carlson, J., & Daehler, K. R. (2019). The refined consensus model of pedagogical content knowledge in science education. In *Repositioning Pedagogical Content Knowledge in Teachers' Knowledge for Teaching Science* (pp. 77–92). Berlin: Springer.

Chan, K. K. H., Rollnick, M., & Gess-Newsome, J. (2019). A grand rubric for measuring science teachers' pedagogical content knowledge *Repositioning Pedagogical Content Knowledge in Teachers' Knowledge for Teaching Science* (pp. 251-269): Springer.

Cohen, L., Manion, L., & Morrison, K. (2013). *Research methods in education* (7th ed.). London: Routledge.

Davidowitz, B., & Potgieter, M. (2016). Use of the Rasch measurement model to explore the relationship between content knowledge and topic-specific pedagogical content knowledge for organic chemistry. *International Journal of Science Education, 38*(9), 1483–1503.

Davidowitz, B., Potgieter, M., & Vokwana, N. (2014). Exploring the relationship between content knowledge of organic chemistry and topic specific PCK. Paper presented at the 22nd annual meeting of the southern African Association for Research in mathematics, Science and Technology Education.

Department of Basic Education. (2011). Curriculum and assessment policy statement physical sciences further education and training grades 10–12. Retrieved from https://www.education.gov.za/Curriculum/CurriculumAssessmentPolicyStatements. Accessed 05 Feb 2019.

Dori, Y. J., & Belcher, J. (2005). How does technology-enabled active learning affect undergraduate students' understanding of electromagnetism concepts? *The Journal of the Learning Sciences, 14*(2), 243–279.

Friedrichsen, P. J., Abell, S. K., Pareja, E. M., Brown, P. L., Lankford, D. M., & Volkmann, M. J. (2009). Does teaching experience matter? Examining biology teachers' prior knowledge for teaching in an alternative certification program. *Journal of Research in Science Teaching, 46*(4), 357–383.

Gall, M., Borg, W., & Gall, J. (1996). *Educational Research An Introduction* (6th).

Gess-Newsome, J. (2015). A model of teacher professional knowledge and skill including PCK: results of the thinking from the PCK summit. In A. Berry, P. Friedrichsen, & J. Loughran (Eds.), *Re-examing pedagogical content knowledge in science education* (pp. 28–42). New York: Routledge.

Geddis, A.N. (1993). Transforming subject-matter knowledge: the role of pedagogical content knowledge in learning to reflect on teaching. *International Journal of Science Education,* 15(6), 673–683

Grossman, P. L. (1991). Overcoming the apprenticeship of observation in teacher education coursework. *Teaching and Teacher Education, 7*(4), 345–357.

Hekkenberg, A., Lemmer, M., & Dekkers, P. (2015). An analysis of teachers' concept confusion concerning electric and magnetic fields. *African Journal of Research in Mathematics, Science and Technology Education, 19*(1), 34–44.

Henze, I., van Driel, J. H., & Verloop, N. (2008). Development of experienced science teachers' pedagogical content knowledge of models of the solar system and the universe. *International Journal of Science Education*, 30(10), 1321–1342.

Henze, I., & Van Driel, J. H. (2015). Toward a more comprehensive way to capture PCK in its complexity. In A. Berry, P. Friedrichsen, & J. Loughran (Eds.), *Re-examing pedagogical content knowledge in science education* (pp. 120–134). New York: Routledge.

Jelicic, K., Planinic, M., & Planinsic, G. (2017). Analyzing high school students' reasoning about electromagnetic induction. *Physical Review Physics Education Research, 13*(1), 010112.

Kaya, O. N. (2009). The nature of relationships among the components of pedagogical content knowledge of preservice science teachers: 'ozone layer depletion' as an example. *International Journal of Science Education, 31*(7), 961–988.

Kind, V. (2009). Pedagogical content knowledge in science education: perspectives and potential for progress. *Studies in Science Education, 45*(2), 169–204.

Kirschner, S., Taylor, J., Rollnick, M., Borowski, A., & Mavhunga, E. (2015). Gathering evidence for the validity of PCK measures. In A. Berry, P. Friedrichsen, & J. Loughran (Eds.), *Re-examining pedagogical content knowledge in science education* (p. 229). New York: Routledge.

Loughran, J., Mulhall, P., & Berry, A. (2004). In search of pedagogical content knowledge in science: developing ways of articulating and documenting professional practice. *Journal of Research in Science Teaching, 41*(4), 370–391.

Magnusson, S., Krajcik, J., & Borko, H. (1999). Nature, sources, and development of pedagogical content knowledge for science teaching. In *Examining pedagogical content knowledge* (pp. 95–132). Berlin: Springer.

Maloney, D. P., O'Kuma, T. L., Hieggelke, C. J., & Van Heuvelen, A. (2001). Surveying students' conceptual knowledge of electricity and magnetism. *American Journal of Physics, 69*(S1), S12–S23.

Mavhunga, E. (2014). Improving PCK and CK in pre-service chemistry teachers. In *Exploring Mathematics and Science Teachers' Knowledge: Windows Into Teacher Thinking* (p. 31). London: Routledge.

Mavhunga, E. (2018). Revealing the structural complexity of component interactions of topic-specific PCK when planning to teach. *Research in Science Education*, 1-22.

Mavhunga, E. (2019). Exposing pathways for developing teacher pedagogical content knowledge at the topic level in science *Repositioning Pedagogical Content Knowledge in Teachers' Knowledge for Teaching Science* (pp. 129-148): Springer.

Mavhunga, E., & Rollnick, M. (2013). Improving PCK of chemical equilibrium in pre-service teachers. *African Journal of Research in Mathematics, Science and Technology Education*, 17(1-2), 113-125.

Mavhunga, E., & Rollnick, M. (2017). Implementing PCK Topic by Topic in Methodology Courses. *Designing and Teaching the Secondary Science Methods Course* (pp. 149-170): Brill Sense.

Mazibe, E. N. (2017). *Teaching graphs of motion: translating pedagogical content knowledge into practice*. Pretoria: (MEd Dissertation), University of Pretoria.

Nilsson, P. (2008). Teaching for understanding: the complex nature of pedagogical content knowledge in pre-service education. *International Journal of Science Education, 30*(10), 1281–1299.

Nilsson, P., & Loughran, J. (2012). Exploring the development of pre-service science elementary teachers' pedagogical content knowledge. *Journal of Science Teacher Education, 23*, 699–721.

Park, S., & Chen, Y. C. (2012). Mapping out the integration of the components of pedagogical content knowledge (PCK): Examples from high school biology classrooms. *Journal of Research in Science Teaching*, 49(7), 922–941.

Park, S., & Suh, J. (2015). From portraying toward assessing PCK: drivers, dilemmas and directions for future research. In A. Berry, P. Friedrichsen, & J. Loughran (Eds.), *Re-examing pedagogical content knowledge in science education* (pp. 104–119). New York: Routledge.

Rollnick, M., Bennett, J., Rhemtula, M., Dharsey, N., & Ndlovu, T. (2008). The place of subject matter knowledge in pedagogical content knowledge: A case study of South African teachers teaching the amount of substance and chemical equilibrium. *International Journal of Science Education*, 30(10), 1365-1387

Rollnick, M., & Mavhunga, E. (2016). Can the principles of topic-specific PCK be applied across science topics? Teaching PCK in a pre-service programme. In N. Papadouris, A. Hadjigeorgiou, & C. Constantinou (Eds.), *Insights from research in science teaching and learning* (pp. 59-72). Cham: Springer

Sağlam, M., & Millar, R. (2006). Upper high school students' understanding of electromagnetism. *International Journal of Science Education, 28*(5), 543–566.

Shulman, L. S. (1986). Those who understand: knowledge growth in teaching. *Educational Researcher, 15*(2), 4–14.

Shulman, L. S. (1987). Knowledge and teaching: foundations of the new reform. *Harvard Educational Review, 57*(1), 1–23.

Van Driel, J. H., De Jong, O., & Verloop, N. (2002). The development of preservice chemistry teachers' pedagogical content knowledge. *Science Education, 86*(4), 572–590.

Veal, W. R., & MaKinster, J. G. (1999). Pedagogical content knowledge taxonomies. *Electronic Journal of Science Education*, 3(4).

Zuza, K., Almudí, J.-M., Leniz, A., & Guisasola, J. (2014). Addressing students' difficulties with Faraday's law: a guided problem solving approach. *Physical Review Special Topics-Physics Education Research, 10*(1), 2–15.