Comparing pedagogical content knowledge across fundamental concepts of electrostatics: A case of three pre-service teachers

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Abstract

It has been recently suggested that pedagogical content knowledge (PCK) has a concept-specific nature, beyond the topic-specific level of PCK. This paper reports a case study of three pre-service teachers' reported PCK about three fundamental concepts within the topic of electrostatics namely: electrostatic force, electric field and electric field strength. The aim of the study was to compare the quality of the PCK of each of the individual participants across these fundamental concepts. Data was collected using a content representation (CoRe) tool and a lesson planning form prescribed by the participants' teacher training institution. A topic-specific PCK model was adopted as the framework for this study. The model asserts that the content of a particular topic is transformed for instruction through five components namely; learners' prior knowledge, curricular saliency, what is difficult to teach, representations including analogies and conceptual teaching strategies. Guided by the model, we designed a rubric to assess the concept-specific PCK of the participants on a four point scale. The results of the study indicated that the PCK of the participants varied across the fundamental concepts of electrostatics, with each participant reporting better PCK for a different concept. The results of the study imply that describing PCK at concept level is appropriate and recommend that PCK should be strengthened at concept level during teacher training to ensure that it develops across all the concepts within a topic.

Keywords: Concept-specific pedagogical content knowledge, - content representations, electrostatics

Introduction

It is commonly understood that pedagogical content knowledge (PCK) exists in different grain sizes namely; subject-specific, domain-specific and topic-specific PCK (Veal & MaKinster, 1999). Recently, it has been argued that PCK also exists at a concept-specific level (Carlson & Daehler, 2019; Smith & Banilower, 2015). The suggestion to consider the concept-specific grain size of PCK assumes that the knowledge and skills needed for teaching various concepts within a topic are not necessarily the same. Because this suggestion is fairly new, explicit evidence of the concept-specific nature of the construct (PCK) is still missing in the literature. We argue that it is important to investigate teachers' PCK at concept level to explore the appropriateness of considering the construct at this grain size. We believe that such an investigation would reveal specific strengths and weaknesses in teachers' knowledge and skills for teaching particular concepts within a topic. As such, researchers and teacher educators may design interventions to target the specific concepts that need development.

In this study, we selected the topic of electrostatics because it has three clearly distinguishable concepts which reveal different learner alternative conceptions according to the literature (e.g. Dega, Kriek, & Mogese, 2013). Furthermore, there is a paucity of information about teachers' PCK in the topic (Melo, Cañada, & Mellado, 2017; Melo-Nino, Cañada, & Mellado, 2017), particularly at concept level. To fill this gap, we compared the quality of three pre-service teachers' (PSTs) PCK across fundamental concepts of electrostatics, guided by the following question:

> How does PCK compare across fundamental concepts of electrostatics for selected pre-service teachers?

The study focused on three concepts namely electrostatic force, electric field and electric field strength, as indicated for the topic of electrostatics within the South African grade 11 curriculum (DoBE, 2011).

Literature review

In the literature, difficulties in understanding the topic of electrostatics have been reported, including those that are related to the fundamental concepts on which this study is based (Li & Singh, 2017). Regarding the electrostatic force, it has been reported that some learners substitute signs of charges into Coulomb's law which they confuse with vector characteristics of forces (Huynh & Sayre, 2018). Furthermore, learners often believe that unequal charges exert unequal forces on each other (Ajredini, Izairi, & Zaijkov, 2013; Maloney, O'Kuma, Hieggelke, & van Heuvelen, 2001). Regarding the electric field for example, learners interpret its lines as objects that are the means of transmission of electrostatic forces between charges (Pocovi & Finley, 2002). In terms of the electric field strength, it has been reported that some learners do not distinguish between the charge that creates an electric field and the charge that experiences the field (Bohigas & Periago, 2010). Consequently, they find it difficult to calculate the electric field strength at a point. It has also been reported that leaners find the concept of an electric field more challenging in comparison to that of an electrostatic force (e.g. Garza & Zavala, 2011).

Despite these well-known learner difficulties, there is a paucity of information about teachers' PCK in electrostatics (Melo et al., 2017; Melo-Nino et al., 2017). Melo and her colleagues explored the initial characterisation of in-service teachers' PCK and their emotions in relation to the construct. In their first study, they formulated concepts in which they explored in-service teachers' PCK without necessarily comparing it across the concepts (Melo-Nino et al., 2017). Instead, they compared it across the participating teachers. They reported that the PCK of the teachers revealed similarities in their knowledge of teaching strategies and content evaluation. However, the teachers' understanding of the importance and the sequence of the selected concepts varied (Melo-Nino et al., 2017). In the second study, they found that the positive and negative emotions of their participants varied across the concepts of the topic (Melo et al., 2017). For example, one of the participants revealed negative emotions, i.e. anxiety, with regard to the concept of the electrostatic force. However, in terms of an electric field, the same participant revealed positive emotions based on his confidence in his knowledge of the content and the practical examples that support its conceptual development. The present study aims to extend their findings by exploring and comparing individual teachers' PCK across the three fundamental concepts of electrostatics.

Since its inception, PCK has drawn the attention of many science education researchers who have adopted and adapted the construct from Shulman's (1987) original conceptualisation to suit their research. Shulman believed that PCK is reflected by teachers' knowledge of learners' difficulties as well as instructional strategies and representations that support the explanation of concepts. Scholars added other components and consolidated them into different models that describe teachers' PCK (e.g. Magnusson, Krajcik, & Borko, 1999; Mavhunga & Rollnick, 2013). According to Carlson and Daehler (2019), the use of different models in PCK research has made it difficult to compare empirical results across topics and contexts. Given this challenge, renowned PCK researchers attended two PCK summits where they shared their conceptions of PCK with the aim of developing a common PCK model. The major products of the summits were the consensus model of PCK (Gess-Newsome, 2015) and later the refined consensus model (RCM) of PCK (Carlson & Daehler, 2019). The RCM recognises that knowledge for teaching can be classified within three realms namely: collective PCK, personal PCK and enacted PCK. Collective PCK is similar to both canonical PCK as described by Smith and Banilower (2015) and indispensable PCK as used by Park and Suh (2015). It refers to the common knowledge that is shared by a community of teachers and that can be applied across different contexts. The next realm describes knowledge that is relatively passive and static while it is unique to individual teachers and contexts, similar to idiosyncratic PCK (Park & Suh, 2015), knowledge-on-action (Park & Oliver, 2008), espoused or planned PCK (Aydeniz & Kirbulut, 2014) and reported PCK (Mazibe, Coetzee, & Gaigher, 2018). When personal PCK is applied during actual teaching, it becomes enacted PCK (Carlson & Daehler, 2019). In this study, we focused on personal PCK, which Gess-Newsome (2015, p. 36) described as the "*knowledge* of, *reasoning* behind, and *planning* for teaching a particular *topic* in a particular *way* for a particular *purpose* to particular *students* for enhanced *student outcomes*". Several instruments have been used to collect data that reflects teachers' personal PCK, for example a Content Representation (CoRe) tool (Loughran, Mulhall, & Berry, 2004) and lesson planning forms (Van Der Valk & Broekman, 1999). A CoRe tool is a document that prompts teachers to (i) identify big ideas or fundamental concepts within a topic and (ii) to indicate ways in which they would transform the concepts for instruction through answering specific prompts.

Theoretical framework

As indicated earlier, Veal and MaKinster (1999) proposed a taxonomy that describes grain sizes of PCK which are recognised in the RCM (Carlson & Daehler, 2019). The RCM also indicates that the different grain sizes of PCK can be found in each of the three realms of the construct. In this study, PCK is explored at the concept-specific grain size in the personal PCK realm. Although the RCM recognises the concept-specific nature of PCK, it does not elaborate on its components at this level. Given this gap, the topic-specific PCK model by Mavhunga and Rollnick (2013) was selected as the conceptual framework for the current study as it includes components representing Shulman's (1987) original ideas. The model describes the transformation of topic-specific content into teachable forms through five components namely; learners' prior knowledge, curricular saliency, what is difficult to teach, representations including analogies and conceptual teaching strategies. Using this model enabled us to explore the participants' reported PCK at concept level in terms of the five topic-specific PCK components. With regard to curricular saliency, we focused on the pre-service teachers' understanding of the place of the fundamental concepts in the curriculum, the sequencing of the concepts and how they are interrelated amongst themselves and with other relevant concepts.

Research methodology

This study followed a qualitative research approach using a multiple case study design to allow an in-depth analysis of the research problem for a small number of participants (Maree, 2010). Three PSTs in their final year of a B.Ed. degree specialising in physics, chemistry and mathematics were purposively and conveniently selected to participate. The pseudonyms Jabulani (Male, 24 years), Vuyelwa (Female, 23 years) and Lungile (Female, 24 years) were assigned to the PSTs to protect their identities. Their reported PCK was inferred using the Content Representation (CoRe) tool (Loughran et al., 2004). In particular, we used prompts from the adapted CoRe tool by Mavhunga and her colleagues (Mavhunga, Ibrahim, Qhobela & Rollnick, 2016) as they are in line with the components of the topic-specific PCK model (See Table 1). Given the nature of this study, we supplied the big ideas to the participants, similar to Melo et al. (2017), to ensure that the analysis of the data is based on the same fundamental concepts. We selected the big ideas according to the fundamental concepts of electrostatics presented in the Grade 11 curriculum in South Africa. These were: electrostatic force, electric field and electric field strength. Before the CoRe tool was completed, the principal author explained the scope of the fundamental concepts to the PSTs, particularly the distinction between an electric field as a concept and the electric field as a physical quantity, similar to the way it is described in the curriculum (DoBE, 2011, p. 85). Briefly, the concept of an electric field refers to the description, demonstration and representation using field lines. The electric field strength refers to the magnitude and the direction of the electric field at a particular point.

During the teaching practice internship, the teacher training institution of the PSTs instructed them to complete planning forms for all the lessons that they present. The forms completed for the topic of electrostatics were collected and analysed to supplement and corroborate the data that had been collected using the CoRe tool. Although the lesson planning form was not structured to explore aspects of PCK, there were sections that revealed relevant pedagogical knowledge that was useful in triangulation. For example, the form requested the PSTs to indicate pre-concepts and new knowledge that would be learnt during the lessons. Furthermore, they were requested to indicate how they would introduce, develop and consolidate the lessons.

Table 1: The adapted CoRe tool for concept-specific PCK in electrostatics

PCK components	Fundamental concepts		
	Electrostatic force	Electric field	Electric field strength
Curricular saliency			
What do you intend learners to know about this key idea?			
Why is it important for learners to know this idea? Refer to the relation of this idea with other topics in the curriculum.			
What else do you know about this idea that you do not intend learners to know yet?			
Learner prior knowledge			
What are the necessary pre-concepts that learners must have before teaching this idea? Also include difficulties in the pre-concepts.			
Knowledge of what is difficult to teach			
What do learners find difficult to understand about this idea and why?			
Representations including analogies			
Which representations would you use to teach this idea and how? Also include the purposes served by the representations.			
Conceptual teaching strategies			
Which conceptual teaching strategies would you use to teach this idea and how?			

To analyse the data, the principal author developed a rubric for reported PCK in electrostatics by adapting pre-existing rubrics (Park, Jang, Chen, & Jun, 2011) (See Appendix A). For expert validation, the rubric was scrutinised by the second and third authors of this paper to ensure that it reflects aspects that are applicable to each component of PCK (Maree, 2010). The competences of the PSTs were quantified on a four point scale with levels; limited (1), basic (2), developing (3) and exemplary (4) (Park et al., 2011). To aid the use of the rubric, we developed an expert CoRe about the fundamental concepts of electrostatics with the aid of the curriculum, academic literature and our experiences of teaching the topic. We regard the expert CoRe as representing collective PCK, being exemplary in the fundamental concepts of electrostatics and the components of PCK while acknowledging that there may be other ways in which the topic of electrostatics can be adequately unpacked for instruction. The data was primarily analysed by the first author and reviewed by the second and the third authors to reach consensus about our interpretation of scoring PCK.

Results and discussion

Table 2 summarises the PCK scores allocated for the three participants across the components of PCK within the fundamental concepts. The last row in the table shows average PCK scores across the fundamental concepts of electrostatics.

Table 2: PSTs' competence across the three fundamental concepts of electrostatics

	Jabulani			Lungile			Vuyelwa		
PCK components	Electrostatic force	Electric field	Electric field strength	Electrostatic force	Electric field	Electric field strength	Electrostatic force	Electric field	Electric field strength
Learner prior knowledge	3	2	2	2	3	2	2	2	3
Curricular saliency	2	2	1	2	3	1	1	2	2
What is difficult to teach?	3	2	2	2	3	3	3	2	4
Representations including analogies	4	2	2	4	3	2	2	3	3
Conceptual teaching strategies	3	2	1	3	3	2	2	3	3
Average PCK score	**3**	**2**	**1.6**	**2.6**	**3**	**2**	**2**	**2.4**	**3**

The overall PCK of the individual participants showed variations across the fundamental concepts of electrostatics. Furthermore, each participant reported better PCK for a different concept as indicated by the shaded columns. Although the raw data were analysed per component of PCK, the discussion of the results combines the components together to paint a holistic picture about the reported PCK of the participants about each fundamental concept. However, prominent components are indicated with single quotation marks where necessary.

Case study 1 – Jabulani

Jabulani's overall PCK about electrostatic forces was scored as 'developing'. He revealed awareness of necessary prior knowledge and identified a major misconception that may hinder successful learning of new concepts. He indicated that learners believe that pieces of paper sticking to a charged ruler are also charged, not realising that they are in fact polarised. However, he did not mention a 'teaching strategy' to uncover and address this particular challenge before explaining new knowledge. In terms of curricular saliency, he recognised the importance of Coulomb's law, stating that it helps learners understand bonding in chemistry. He also reported a fruitful 'demonstration' for Coulomb's law using the interactions between a charged ruler and pieces of paper. He indicated that he would (i) vary the charge on the ruler by rubbing slightly or vigorously and (ii) vary the distance between the ruler and the pieces of paper while learners observe the differences in the interactions. He also revealed awareness of 'major difficulties' and devised 'strategies' for addressing them. He mentioned that learners confuse signs of charges with vector characteristics and that they disregard the influence of the magnitude of the charges on the electrostatic force. The second difficulty referred to instances where two charges exert forces on a third charge, whereby learners think the closest charge exerts the strongest force regardless of its magnitude. To address these difficulties, he indicated that he would firstly calculate the magnitudes of the forces, while cautioning against the substitutions of signs into Coulomb's law before 'representing' them with vector diagrams. The diagrams would be constructed in proportion to the magnitudes of the forces before they are used to determine the magnitude and the direction of the resultant electrostatic force on the reference charge.

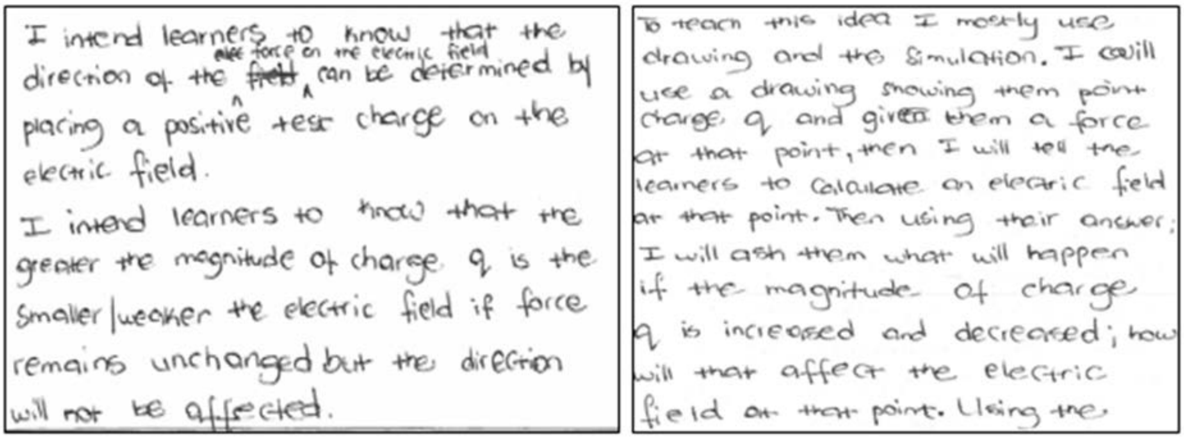
For the concept of an electric field, he showed poorer PCK. He revealed awareness of the prior knowledge of charge interactions without identifying any challenges that may hinder the learning of new concepts. He also overlooked the fact that the 'representation' which he mentioned can also demonstrate an electric field:

> *The difficult thing in teaching this idea is finding real life examples that you can use to demonstrate the electric field, one cannot use a ruler and a piece of paper just like in demonstrating the electrostatic force.*

Nevertheless, he suggested an adequate explanation of the direction of electric field lines around a point charge, by 'drawing a diagram' showing a source charge and a positive test charge. He would then ask learners to indicate the path that would be taken by the positive test charge, i.e. the direction of the electric field. In terms of curricular saliency, he mentioned that he would start by discussing aspects of the electric field strength; the formula $E = k\frac{Q}{r^2}$ in particular. He justified this sequence, stating that it would help him draw electric field patterns accurately in such a way that reflects the relationships described by the formula. For example, a bigger charge would be surrounded by more field lines. He also reported 'difficulties' that were restricted to the errors that learners make in their drawings of electric field patterns. The cause of these difficulties, as he added, is that some textbooks do not draw the patterns correctly.

For the third concept, the electric field strength, Jabulani's overall PCK was inadequate. He revealed awareness of the necessary prior knowledge for the electric field strength, including the preceding fundamental concepts. However, he did not identify difficulties in the 'prior knowledge' except mentioning that learners do not understand why vectors have directions while scalars do not. In terms of curricular saliency, Jabulani reported that the importance of understanding the electric field strength is that "it helps them (learners) in answering multiple choice questions on electrostatics", but such reference to the general benefit of education does not reflect curriculum saliency is regarded as a weakness by Rollnick and her colleagues (Rollnick, Bennett, Rhemtula, Dharsey & Ndlovu, 2008). His 'general strategy' for teaching the new concept was centralised around the formula E = F/q in a manner that promotes algorithms rather than conceptual understanding (Gaigher, Rogan, & Braun, 2007). He suggested showing learners that an electric field is a vector because it is a quotient of a vector and a scalar quantity. He also mentioned that he would teach learners that the magnitude of the electric field at a point is inversely proportional to that of the test charge placed at that point (Fig 1), which reveals that he confused the roles of the source and the positive test charge (Bohigas & Periago, 2010). Jabulani also suggested using representations in the form of drawings and simulations to support the discussion of the incorrect concept (See Fig. 1). It seems that Jabulani promoted algorithms possibly because of his restricted knowledge of the content, similar to a finding by Rollnick et al. (2008).

Fig 1: Jabulani's misconception about the electric field strength



Case study 2 – Lungile

Lungile's PCK about the concept of an electrostatic force across the components ranged from 'basic to developing'. She revealed awareness of the necessary prior knowledge including charges, vectors and forces. She also identified a misconception in the prior knowledge, stating that learners do not understand that it is only electrons that are transferred during charging. To address this difficulty, she suggested using a 'simulation' that shows the transfer of electrons during charging by friction. She indicated a fruitful 'demonstration' of Coulomb's law using a charged ruler and pieces of paper, varying the distance between the ruler and the pieces of paper while learners observe how the interactions change. In terms of curricular saliency, she referred to the interrelatedness between Newton's law of universal gravitation and Coulomb's law because they both describe inverse square relationships between interacting objects. She was also aware that learners might find it 'difficult' to determine the direction of the electrostatic force because they would substitute signs of charges into Coulomb's law. She devised the following 'strategy' for this difficulty:

> *Here the interaction between charges is really important, whether the charges are like charges or whether they are unlike charges. Then forces that tend to move the charge in the same direction are added, while forces that act in the opposite direction are subtracted.*

With regard to the electric field, she identified magnetic fields as part of the necessary 'prior knowledge' and mentioned a possible misconception, stating that "learners mostly confuse magnetism and electric field, being able to differentiate between the two is difficult for them." This is a major misconception that is documented in the literature (e.g. Hekkenberg, Lemmer, & Dekkers, 2015). She devised a 'teaching strategy' that addresses the misconception, suggesting asking: "why is it that nothing happens when you put the ruler underneath [a piece of paper with iron filings] instead of magnets?" This question suggests that she would use a 'charged ruler and a magnet' to show the difference in the behaviour of iron filings. In terms of curricular saliency, she recognised the importance of electric fields, stating that they help learners understand what makes charges interact and flow in electric circuits. Lungile also revealed awareness of difficulties in the new knowledge. She indicated that it is important "to make learners understand that field lines do not indicate the flow of any physical quantity but that there is only a force field”. This is a major ‘difficulty’ documented in the literature, i.e. that learners regard electric field lines as the means of the transmission of the electrostatic interaction between charges (Pocovi & Finley, 2002). Overall, she displayed ‘developing’ PCK about this concept.

In contrast, Lungile’s PCK about the electric field strength was ‘basic’. She revealed awareness of prior knowledge, for example vectors and their additions. However, she did not indicate any challenges in the prior knowledge. In terms of curricular saliency, she indicated that the importance of electric field strength is that “it is the foundation of physics concepts such a Newtonian mechanics.” She did not provide clarity in this regard. Perhaps she meant that an electric field is a foundational concept in physics similar to Newtonian mechanics. She also referred to 2D vector diagrams showing electric field strengths. In this regard, she revealed restricted knowledge of the South African curriculum which limits electric field problems to one dimension. Nevertheless, she was aware of ‘major difficulties’ in the new concepts. She indicated that learners find it difficult to determine the direction of an electric field at a point. Instead, they include signs of charges in their calculations which they confuse with vector characteristics. To address the first difficulty, she indicated that she would represent the electric field at a point using ‘drawings of vector diagrams’. However, she did not explain how the direction of the electric field would be determined in order to represent it with a vector diagram. Generally, she did not report strategies that she would use to teach this fundamental concept.

Case study 3 – Vuyelwa

Overall, Vuyelwa’s reported PCK about electrostatic forces was ‘basic’. She revealed awareness of prior knowledge, for example charge interactions without identifying challenges that may hinder the learning of new concepts. She also did not report any ‘strategy’ to demonstrate Coulomb’s law apart from stating the law in words. Nevertheless, she was aware of ‘major challenges’ related to electrostatic forces. She mentioned that learners find it difficult to determine the directions of electrostatic forces. They substitute signs of charges into Coulomb’s law and interpret the sign of the final answer as the direction of the force. She also added that they believe bigger charges exert stronger forces on smaller ones, a misconception about Newton’s third law (Maloney et al., 2001). Vuyelwa devised ‘teaching strategies’ for addressing these difficulties. Regarding the first difficulty, she would instruct learners to “look at the charges and choose a positive direction” instead of substituting signs. Regarding the application of Newton’s third law, she wrote: “demonstration of a pencil being pushed to roll and ask learners will the pencil stop. If yes or no why and that could explain the Newton third law.” This ‘demonstration’ is misplaced, as it appears to be better suited for Newton’s first and second law. She also exposed her own misunderstanding of the relationship between an electrostatic force and the electric field in terms of sequencing in curricular saliency. She justified the importance of electrostatic forces as follows: “forces of particles produce the electric field and later will work on the electric field and the electric field as a vector,” suggesting the belief that an electrostatic force creates an electric field.

Her overall PCK about the electric field was also ‘basic’. She recognised magnetic and gravitational fields as being part of the ‘prior knowledge’ necessary to understand the electric field. However, she did not indicate challenges in the prior knowledge. Nevertheless, in terms of curricular saliency, she indicated that the importance of learning about the electric field is that it helps learners comprehend why charged objects interact. She also appreciated the use of a ruler-paper demonstration as a representation that supports the description of an electric field as a region of space where a charge experiences a force. Her knowledge of ‘difficulties’ with the new concepts was restricted to the errors that learners make in their drawings of electric field patterns. She pointed out that the errors are caused by the fact that an electric field is invisible and three dimensional. As such, she suggested the use of ‘iron filings’ to help learners visualise a field and its representation using field lines.

In contrast, her PCK about the electric field strength was well ‘developed’. She recognised that a lack of understanding of the interpretation of field lines in their ‘prior knowledge’ could hinder successful learning of new concepts. She said “field lines are drawn closer where the field is stronger and learners tend to think that it is the same throughout”, suggesting that learners think that electric fields are always uniform. This is a ‘major difficulty’ that is documented in the literature (e.g. Törnkvist, Pettersson, & Tranströmer,1993). Törnkvist and colleagues reported that learners do not infer the strengths of electric fields from the density of field lines, as such; they believe that the strength remains the same along the same field line (Saarelainen, Laaksonen, & Hirvonen, 2006). However, she did not indicate ‘strategies’ for addressing this challenge. In terms of curricular saliency, she indicated that the concept of the electric field strength helps learners understand electromagnetism, which is the next topic after electrostatics according to the curriculum. She also revealed an awareness of other ‘major difficulties’ and included the gate keeping concepts. She indicated that learners find it difficult to determine the direction of the electric field at a point so they can represent it with a vector diagram. The cause of this difficulty, as she indicated, is that learners forget about the directions of the electric field lines. Furthermore, they find it difficult to determine the resultant electric field at a point for various reasons. Firstly, they add the magnitudes of the separate fields without considering their directions. Secondly, they believe that the resultant electric field halfway between two equal but opposite charges is zero and that it reinforces if the charges have the same polarity (Li & Singh, 2017). To address the difficulties, she indicated that she would “present the direction of the electric field at a point using the electric field lines drawn on the board.” This implies that she would ‘draw’ an electric field pattern and instruct learners to focus on the field line that passes through the point as it indicates the direction of the resulting electric field at that point.

Concluding remarks

Comparing the quality of the individual PSTs’ reported PCK across the fundamental concepts of electrostatics revealed that it varied from one concept to another. Furthermore, the variations in PCK quality were predominantly unique to the PSTs rather than to the concepts, with each teacher reporting adequate PCK for a different concept of electrostatics. Thus, the results support the notion that PCK has a concept-specific nature following from its variation in quality at concept-specific level (Carlson & Daehler, 2019; Smith & Banilower, 2015). Currently there is no model of PCK components at the concept-specific level; however, the findings of this study suggest that the components of topic-specific PCK (Mavhunga & Rollnick, 2013) can be used to investigate the quality at the concept-specific level.

In the present study, we did not investigate the causes of the variations. However, we speculate that they may be caused by the nature of the concepts, the variations in the depth of the conceptual knowledge and the “apprenticeship of observation” (Grossman, 1991, p. 345). The apprenticeship of observation refers to PSTs’ preconception of teaching practice obtained from years of observing their teachers in action. In terms of content knowledge, Vuyelwa and Jabulani’s conceptual understanding seemed to be restricted in some aspects of the electrostatic force and the electric field respectively. For Vuyelwa in particular, the representation that she selected for demonstrating the application of Newton’s third law was inadequate and reflected a limited understanding of the law. Because we did not explicitly explore the content knowledge of the participants, we recommend a study that investigates the relationship between content knowledge and PCK at concept level.

The implication for teacher education is that content knowledge and PCK must be strengthened at concept-specific level to ensure that the entirety of a particular topic is addressed. Further research may also be undertaken to investigate fruitful teaching methods for teacher education regarding concept-specific PCK.

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Appendix A: The rubric for scoring the reported PCK of the PSTs

	Limited	Basic	Developing	Exemplary
Learners' prior knowledge	No reference to prior knowledge.	Reference to a few pre-concepts. Difficulties and gaps are not specified.	Reference to some pre-concepts. Gaps and difficulties are limited to a few pre-concepts.	Reference to many pre-concepts. Gaps and difficulties in the pre-concepts are specified.
Curricular saliency	No reference to new concepts prescribed in the curriculum. No indication of links between prior knowledge and new concepts. No indication of the importance of new concepts.	Reference to a few concepts prescribed in the curriculum. Links between the new concepts and prior knowledge are implied. The importance of concepts does not include scaffolding.	Reference to most of the concepts prescribed in the curriculum. Shows links between the new concepts and prior knowledge. The importance of concepts includes scaffolding without specifying new knowledge.	Reference to all concepts prescribed in the curriculum. Explains links between new concepts and prior knowledge. The importance of concepts includes scaffolding into specific and relevant future concepts.
What is difficult to teach?	No indication of learners' difficulties. Gate keeping concepts are also missing.	An indication of a few areas of learners' difficulties. The difficulties are broad and not explained. Gate keeping concepts are missing, minor or generic, e.g. "learners' mathematical knowledge is lacking".	An indication of some of the areas of learners' difficulties. The difficulties are sufficiently explained. Gate keeping concepts are specified for some of the difficulties.	An indication of many areas of learners' difficulties. The difficulties are extensively explained and specified. Gate keeping concepts are linked with misconceptions.
Representations including analogies	Representations are not reported.	Reference to a single kind of representation. No indication of how the representation works. No indication of concepts supported by the representation.	The teacher mentioned one or more suitable representation. The teacher explained how the representations work. The representations are predominantly used for one purpose; to support conceptual change OR conceptual development.	The teacher identified several suitable representations. The teacher explained how the representations work as well as the concepts that they support. The representations are used to support conceptual change as well as conceptual development.

Conceptual teaching strategies	Teaching strategies are listed but not explained. There are no connections between the strategies and the key ideas. No strategy to uncover prior knowledge. No strategy to uncover difficulties. No strategies to support conceptual change and development through the use of representations.	Teaching strategies are listed but only a few are explained. The strategies seldom refer to uncovering prior knowledge. The strategies seldom refer to uncovering learners' difficulties. The strategies exclude the use of representations or the representations do not appear to be effective. There is no evidence of cognitive involvement of learners.	Several teaching strategies are mentioned and adequately explained. The strategies uncover some prior knowledge. The strategies uncover some learner difficulties. The strategies include representations that support conceptual change and development. There is evidence of cognitive involvement of learners.	Several teaching strategies are reported and extensively explained. The strategies uncover most prior knowledge. The strategies uncover most learner difficulties. The strategies include representations that serve various purposes; addressing difficulties in the prior knowledge, new concepts and supporting conceptual development of new knowledge. Learners are cognitively involved in activities.