MODESTUM EURASIA Journal of Mathematics, Science and Technology Education, 2023, 19(3), em2241
ISSN:1305-8223 (online)
OPEN ACCESS Research Paper https://doi.org/10.29333/ejmste/13023

Exploring dynamic pedagogical content knowledge across fundamental concepts of electrostatics

Ernest Nkosingiphile Mazibe [1*], Estelle Gaigher [2], Corene Coetzee [2]

[1] Department of Science and Technology Education, College of Education, University of South Africa, Pretoria, SOUTH AFRICA
[2] Department of Science, Mathematics and Technology Education, Faculty of Education, University of Pretoria, Pretoria, SOUTH AFRICA

Received 22 September 2022 ▪ Accepted 28 December 2022

Abstract

This paper reports a case study that explored teachers' dynamic pedagogical content knowledge (PCK) across three big ideas of electrostatics namely the electrostatic force, electric field, and electric field strength. Two pre-service and two in-service teachers participated in the study. The refined consensus model of PCK was adopted as the theoretical framework for the study. We studied PCK as enacted during classroom teaching using observations and interviews. Data was analyzed alongside a four-point scale grand PCK rubric used to score the competence of the teachers for every big idea. The results showed that PCK of the teachers varied across the big ideas, which is attributed to the nature of concepts, as well as teachers' content knowledge in each. The findings imply that pre-service teacher education programs should involve focus on teaching specific concepts to support the development of holistic PCK for a topic.

Keywords: pedagogical content knowledge, fundamental concepts, electrostatics

INTRODUCTION

This paper reports empirical research findings of a case study that investigated teachers' dynamic pedagogical content knowledge (PCK) (Shulman, 1986) enacted when teaching electrostatics. It is important that teachers acquire appropriate PCK to teach electrostatics, as literature shows that learners find the topic difficult to understand (e.g., Li & Singh, 2017), particularly the concept of an electric field and its strength in relation to that of electrostatic forces (Garza & Zavala, 2013).

In the South African science curriculum, the topic of electrostatics is taught extensively in grade 11 where it is presented in terms of three concepts, namely electrostatic force, electric field, and electric field strength (Department of Basic Education [DoBE], 2011). *Electrostatic forces* describe the strengths of attraction and repulsion that charges have on each other. The *electric field* describes the region of space where charges experience forces while the *electric field strength* indicates the force experienced per unit charge ($E=F/q$) at a specific point of interest.

Recently, researchers have proposed that PCK has a concept specific nature (e.g., Carlson & Daehler, 2019) in addition to its discipline and topic specific grainsizes (Veal & MaKinster, 1999). The notion of concept specific PCK is not entirely new. In fact, it has been implicit in many studies that investigated PCK at topic level. For example, the content representation (CoRe) tool by Loughran et al. (2004) portrays teachers' topic specific PCK in terms of the big ideas of the topic, which are the major concepts on which the topic is based. Researchers have been concerned with teachers' overall PCK instead of studying it per concept. In the present study, the fundamental concepts of electrostatic (electrostatic force, electric field, and electric field strength) are regarded as the big ideas of the topic, and we assume that the quality of teachers' PCK for teaching this topic may vary across the concepts. Previously, we have found a variation in teachers' static PCK across the same fundamental concepts (Mazibe et al., 2020). However, we understand that static PCK is not a true reflection of dynamic PCK (Chan & Hume, 2019). Therefore, the present study aims to expand the understanding of concept specific PCK by exploring its dynamic forms in a real classroom situation

✉ maziben@unisa.ac.za **(*Correspondence)** ✉ estelle.gaigher@up.ac.za ✉ corene.coetzee@up.ac.za

Contribution to the literature

- The study provides empirical evidence that shows the quality of teachers' dynamic PCK varying across the fundamental concepts of electrostatics.
- The results therefore support the concept specific nature of PCK that has been proposed in the literature.
- The study also found PCK variations across the fundamental concepts to be related to the nature of the concepts and the level of teachers' content knowledge about the concepts.

across the fundamental concepts of electrostatics. The following research question was formulated:

> How do selected teachers' dynamic PCK compare across the fundamental concepts of electrostatics and how can variations be explained?

In the present study, we focused on the dynamic aspects of PCK enacted during actual teaching, in agreement with Alonzo et al. (2012) who argued that they' reflect PCK as it is used in practices associated with teaching, rather than manifestations that are further removed from the classroom–such as interviews and paper-and-pencil assessments' (p. 1216).

LITERATURE REVIEW

The Static and Dynamic Nature of Pedagogical Content Knowledge

When reflecting on his original conception of PCK, Shulman (2015, p. 10) indicated that it 'was relentlessly intellectual; it was attentive to the life of the pedagogical mind, and it did not attend sufficiently to pedagogical *action*' (p. 10). This was after other researchers had already proposed that PCK encompasses knowledge and practice (e.g., Park & Oliver, 2008), which is static and dynamic in nature respectively (Alonzo & Kim, 2016). Gess-Newsome's (2015) description of PCK refers to the static 'knowledge of, reasoning behind, and planning' and the dynamic' act of teaching' (p. 36).

The static and dynamic forms of PCK are different yet related because of the contexts in which they are expressed. Teachers' static PCK is expressed in planning in an environment that is free of the classroom situation and has received criticism for obscuring other crucial aspects of teacher knowledge, particularly the skills needed to carry out classroom instruction (Grossman et al., 2009). Consequently, static PCK is commonly regarded as being less authentic (Chan & Hume, 2019). However, many researchers found that teachers' dynamic PCK was predominantly restricted when compared to the static PCK (e.g., Barendsen & Henze, 2019) while others reported enhanced practice compared to what the static PCK had suggested (e.g., Mavhunga & van der Merwe, 2020). Nevertheless, the importance of static forms of PCK cannot be downplayed because they inform lesson preparation (Alonzo & Kim, 2016), which is the foundation of actual teaching. As stated by Alonzo et al. (2019), when involved in the act of teaching, teachers formulate dynamic PCK that is suitable for the immediate situation by referring to their static PCK. Unfamiliar teaching situations trigger teachers' on-the-spot decisions that are shaped by reflections-on-action (Barendsen & Henze, 2019) and may also prompt a teacher's reflection-in-action after the lesson which could develop their static PCK for future lessons (Alonzo et al., 2019).

The Classroom Situation: The Location of Dynamic Pedagogical Content Knowledge

According to Barendsen and Henze (2019), teachers' decisions are shaped by personal and situational factors. The classroom situation corresponds with the latter and presents factors that are different from what teachers get exposed to when planning for a lesson. During planning, the expression of PCK is shaped by long term decisions whereas during teaching, the decisions are short term. Factors that shape teachers' short-term decisions during teaching have been investigated in instances where static and dynamic PCK showed variations (e.g., Barendsen & Henze, 2019; Mavhunga & van der Merwe, 2020). The interaction between teachers, learners, and the content has been identified as one of the reasons for the variations. For example, Henze and Barendsen (2019) reported that the reluctance of learners to engage with content saw the teacher reverting to a traditional authoritative approach after having declared a constructive strategy in his planning. In contrast, when learners engaged with the content through answering and asking questions of their own, teachers were prompted to reveal aspects of their PCK that were not explicit in their planning (e.g., Mavhunga & van der Merwe, 2020; Park & Oliver, 2008). Furthermore, when practical demonstrations did not produce the expected results, the teachers provided remedial explanations (Park & Oliver, 2008). It is evident that dynamic PCK is different from static PCK as it is expressed in an active classroom situation, which warrants the need for the present study.

THEORETICAL BACKGROUND

The present study adopted the refined consensus model (RCM) of PCK (Carlson & Daehler, 2019). The model describes PCK in three realms namely, collective PCK (cPCK), personal PCK (pPCK), and enacted PCK (ePCK). The cPCK realm describes knowledge for

Table 1. Summary of scores per big idea allocated to teachers' competence in each component of PCK: limited (1), basic (2), developing (3), & exemplary (4)

PCK components: Knowledge and skills related to …	Vuyelwa			Jabulani			Merriam			Patrick		
	EFO	EFI	EFS	EFO	EFI	EFS	EFO	EFI	EFS	EFO	EFI	EFS
Curricular saliency	2	2	3	3	3	2	3	1	1	3	2	2
Learners' understanding of concepts	2	2	3	3	2	3	2	2	2	2	2	1
Conceptual teaching strategies including representations	2	2	3	3	2	2	2	1	1	2	2	2

Note. EFO: Electrostatic force; EFI: Electric field; EFS: Electric field strength

teaching that is commonly shared by teachers, teacher educators, and researchers. The pPCK and ePCK realms describe knowledge that is unique to individual teachers, with the former serving as the reservoir of static PCK while the latter is dynamic. Furthermore, RCM makes it explicit that it is ePCK that impacts learning directly given its proximity to learners. Using this understanding, the present study is conceptualized within the realm of ePCK. RCM also recognizes the concept specific grainsize of PCK, the level at which the present study is conducted as it focuses on fundamental concepts of electrostatics.

In order to characterize teachers' dynamic PCK in each fundamental concept of electrostatics, the components of the grand PCK rubric (Chan et al., 2019) were adopted as the analytical framework. The components are knowledge and skills related to

(1) curricular saliency,

(2) learners' understanding of concepts, and

(3) instructional strategies including representations.

The grand rubric also refers to the integration of the components as well as the pedagogical reasoning that shapes teachers' decisions (Chan et al., 2019). For this study, we focused on the three components of PCK given their prominence in the literature. Briefly, the component of curricular saliency describes the selection, connection, and coherence of big ideas among themselves and with pre-concepts, and the accuracy of content. Learners' understanding of concepts refers to describing learners' understanding as well as eliciting and assessing student difficulties and misconceptions. Conceptual teaching strategies refers to the selection and use of suitable instructional approaches while employing a variety of representations.

METHODOLOGY

This study followed a qualitative research approach using a case study research design. A sample of two pre-service and two in-service teachers was purposively and conveniently selected to participate in the study for an in-depth analysis of their PCK. The sample was selected based on research evidence that pre-service teachers tend to lack PCK compared to their experienced counterparts (Kind, 2009). The four teachers were working independently in separate schools. The pre-service teachers, given the pseudonyms Vuyelwa and Jabulani were fourth year BEd students specializing in physics, chemistry, and mathematics. The in-service teachers, with pseudonyms Merriam and Patrick, respectively acquired a national diploma in analytical chemistry and a BSc honors in chemistry after which both pursued a postgraduate certificate in education (PGCE) that qualified them to teach physical sciences. At the time of the data collection, they had six- and ten-years teaching experiences respectively.

Data was collected using classroom observations and interviews as the focus of the study was on teachers' dynamic PCK. Each teacher was observed teaching the entire topic of electrostatics as the study aimed to compare their dynamic PCK across the fundamental concepts of the topic. The number of lessons observed varied across the teachers depending on their pace. For triangulation, interviews were used to corroborate the data that was collected using observations.

Given the aim of the study, it was necessary to develop a scoring rubric that describes criteria for rating PCK competence across the fundamental concepts of electrostatics. Following the adoption of RCM as the framework for the study, the scoring rubric was developed using the grand PCK rubric (Chan et al., 2019), adapted to suit the topic of electrostatics (**Appendix A**). The rubric describes criteria at four levels that reflects teachers' competence in the components of the grand rubric: limited (1), basic (2), developing (3), and exemplary (4). The indicators describing the levels of competence were inferred from pre-existing rubrics (e.g., Park et al., 2011). For expert validation, the rubric was scrutinized by the second and third authors of the present paper. The data was primarily analyzed using in-depth qualitative analysis which was followed by the allocation of a score that describes the level of competency that the teachers displayed for each fundamental concepts in the components of the grand PCK rubric. Furthermore, the analysis of the data and the allocation of the scores were primarily conducted by the principal author and validated by the second and third authors. In instances where there were disagreements, consensus was negotiated through discussions.

RESULTS

A summary of the teachers' PCK scores across the big ideas is provided in **Table 1**. The results are presented per case whereby the big ideas are discussed under each component of PCK while describing similarities and differences in the way they were presented.

In the discussion of the results, where necessary, direct quotes from the rubric are included to justify scores.

Case Study 1–Vuyelwa

Knowledge and skills related to curricular saliency

Vuyelwa's lessons revealed aspects of curricular saliency associated with the use of pre-concepts as the foundation for subsequent knowledge. Regarding *electrostatic forces*, she revisited some pre-concepts while excluding others, for example trigonometric ratios as she did not determine directions of resultant forces in 2D due to a lack of content knowledge, as she stated:

> Honestly, I did not know [how to determine the directions of resultant forces]. Even myself I did not how can I say what the direction is. So, I thought let me leave it just before I confuse myself and the learners too. One of the learners did ask' ma'am what is the direction', I said,' no, just go and do it'.

Regarding the *electric field*, although she revisited the pre-concepts of magnetic fields, she described them and their interrelatedness with electric fields inadequately. She said:

> Remember in grade 10 we used iron filings to observe an electric field … I mean a magnetic field around a magnet bar? That's how he [Faraday] was able to see the electric fields around a charged object. He said thus electric field can be observed by placing a grain of materials such as a semolina or iron filings.

In this regard, we note the effect of content knowledge in the exclusion and inadequate discussion of pre-concepts and the corresponding subsequent knowledge. The two fields are different and can be demonstrated using different particles, iron filings for magnetic fields and semolina seeds for electric fields. Nevertheless, the pre-concepts of charge interactions were used adequately to determine directions of *electrostatic forces* and *electric field* lines using a positive test charge. As such, a basic (2) score was allocated for both big ideas because only a few concepts were 'developed from or linked with corresponding pre-concepts.' Regarding the *electric field strength*, pre-concepts were predominantly used adequately to develop new knowledge. For example, Coulomb's law was adequately used alongside the definition of an electric field at a point (E=F/q) to derive the formula $E = k\,\frac{Q}{r^2}$. Furthermore, the pre-concepts of a positive test charge and electric field patterns were used to determine directions of electric fields at a point before superimposing them to obtain their resultants in terms of magnitude and direction alongside a specified frame of reference. In this regard, Vuyelwa was allocated a developing (3) score because links between pre- and new concepts were predominantly evident.

Knowledge and skills related to learners' understanding of concepts

Vuyelwa uncovered and addressed learners' difficulties some degree of variation across the big ideas. Regarding *electrostatic forces*, a learner revealed a major misconception, stating that whenever a rubbed plastic ruler does not attract pieces of paper, it is because the pieces of paper carry an opposite charge, resulting in a repulsion. We observed that Vuyelwa did not acknowledge and address the misconception. When calculating the magnitudes of *electrostatic forces*, she emphasized that signs of charges must be excluded. However, the reason for the exclusion was misleading, stating that:' the negative [sign] only indicates that the charge is negative. If you substitute [it in Coulomb's law] your answer is going to be negative. Do we have a negative force?' Forces can be negative depending on chosen frame of reference. The issue is that learners would think that the force is in the negative direction without consulting with the reference frame. Regarding the *electric field*, she potentially perpetuated the misunderstanding of the poor distinction between electric and magnetic fields (Hekkenberg et al., 2015) when she said they can both be depicted using iron filings and/or semolina seeds. Nevertheless, she addressed challenges associated with drawing and interpreting electric field patterns, emphasizing that field lines should neither touch nor cross and that their density represent the strength of the field. Vuyelwa was therefore allocated a basic (2) score for both the *electrostatic force* and *electric field* because only 'a few areas of learners' difficulties' were addressed.

Regarding the *electric field strength*, she addressed major challenges that are documented in the literature. She made it explicit that a test charge [q] does not affect the electric field strength [E] of a source charge [Q]. In the literature, it is documented that learners associate the electric field at a point with the charge placed at that point (Li & Singh, 2017). She also distinguished between the source and the test charge and explained how they are used to calculate the magnitude of the electric field using E=F/q and $E = k\frac{Q}{r^2}$. This explanation was particularly important because learners tend to confuse the roles of the two charges in electrostatics (Bohigas & Periago, 2010). She was therefore allocated a developing (3) score for addressing 'some areas of difficulty while expanding on explanations.'

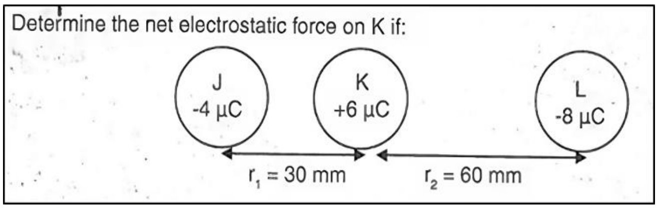

Figure 1. One of the problems of electrostatic forces solved by Vuyelwa (Bernardo et al., 2012)

Knowledge and skills related to conceptual teaching strategies including representations

Generally, Vuyelwa's conceptual teaching strategies were characterized by questions and explanations while using representations with some variation across the big ideas. Regarding *electrostatic forces*, she involved learners by asking them to study charge interactions to determine directions of the forces. Some of the questions were 'are the (interacting) charges like or unlike? Charge K will (therefore) go to the …?' Once the directions were obtained, she represented them using vector diagrams which she labelled adequately, e.g., $F_{L\ on\ K}$. Although the directions of the forces were evident in the diagrams, Vuyelwa did not write them down next to their magnitudes. Instead, she described charge interactions, for example '$F_{L\ on\ K}$=240 N attraction.' This is how she determined the resultant forces in one of the problems (**Figure 1**).

> Vuyelwa: The net force will be $F_{J\ on\ K}$+$F_{L\ on\ K}$, then you add them. But this one [$F_{J\ on\ K}$] is to the left so I expect the answer to be–240 N plus positive 120 N … then you get your answer [the resultant force], it is going to be 120 N. I know it is negative, but we do not have a negative force right? So the answer (direction of the resultant force) is going to be 'repulsion'.
>
> Learners: Repulsion? How is it repulsion?
>
> Vuyelwa: Because it is negative … opposite direction means? Repulsion!
>
> Learners: Mhm. I do not understand.
>
> Vuyelwa: The direction will be repulsion because this one (while pointing at J) goes to the…like they do not come towards the positi… the negative charge. They go away you see that? Let's do other examples you will understand.

Vuyelwa added the forces correctly using the vector diagram. However, she could not deduce the direction of the resultant force, associating the negative sign with repulsion.

When discussing *electric fields*, she drew a diagram showing a source charge with several positive test charges around it to explain the directions of electric field lines. However, some of her questions and explanations were not well structured as shown in the dialogue:

> Vuyelwa: How will the electric field look like if I place a positive test charge there (next to the positive source charge)? (Silence) It is positive, the main charge is also positive. How will the electric field lines look like?
>
> Learner A: Ma'am (madam), I think they will move apart.
>
> Learner B: They will never touch.
>
> Vuyelwa: But if you are saying that they are repelling, how do I draw them (field lines)? Here, here, or here (pointing at random points around the source charge)?
>
> Learner B: The big one with a line going like down and the small one with a line going up.
>
> Vuyelwa: We said this one is positive and this one is positive, so they repel. So, the direction of the electric field will go that way (she drew an arrow showing the force on the positive test charge).

The questions did not focus the attention of learners on the force acting on the positive test charges to indicate the direction of the electric field. Furthermore, she mentioned that the electric field 'go[es] that way' because of a repulsion without highlighting the role of the positive test charge. Nevertheless, once the electric field patterns were developed from the discussion, she confirmed them using a simulation. Vuyelwa was allocated a basic (2) score for *electrostatic forces* and *electric fields* for using a representation while involving 'learners in the lesson through questions.'

Regarding the *electric field strength*, after deriving the formula $E = k\frac{Q}{r^2}$, she explained that the field is stronger where the field lines are closely packed, i.e., near the charge. She also used a simulation to show that the vector diagrams extending from the test charge, representing the electric field strength decreased with distance in size, indicating that it was weakening. When solving problems involving directions of electric fields at a point, some of her questions were not clear. Nevertheless, upon realizing some uncertainty from the learners, she changed to another approach to support learners. Once the directions of the electric fields were determined, she represented them using vector diagrams before calculating their magnitudes. Differently from the case with *electrostatic forces*, Vuyelwa used a frame of reference to specify the directions of electric fields next to their magnitudes, e.g., '$E_{p,x}$ = 2.13 x 10^4 N.C^{-1} to the right.' This enabled learners to determine the magnitudes and directions of the resultant electric field at the reference point. According to the rubric, a developing (3) score was allocated for using 'various representations while explaining important and difficult concepts.'

Case Study 2–Jabulani

Knowledge and skills related to curricular saliency

Jabulani revisited most pre-concepts for *electrostatic forces* to support the discussion of new knowledge. For example, he used charge interactions to determine directions of electrostatic forces before representing them using vector diagrams. Furthermore, he used the theorem of Pythagoras and trigonometric ratios to determine magnitudes and directions of resultant forces in 2D. As such, a developing (3) score was allocated for 'discussing most of the prescribed ideas' while linking them 'with corresponding pre-concepts.'

Regarding the *electric field*, he did not revisit the pre-concepts of magnetic fields as recommended in the curriculum. Nevertheless, he used the pre-concepts of charge interactions to explain directions of electric field lines using a positive test charge. Jabulani's case also revealed alternative sequencing when he discussed parts of the *electric field* and the *electric field strength* interchangeably. For example, after describing an electric field, he then defined it ($E=F/q$) and derived the formula $E = k\frac{Q}{r^2}$ before drawing electric field patterns. During the interview, he explained the rationale behind his decision, stating that he wanted to draw electric field patterns that resemble the formula derived earlier. Indeed, bigger charges had many field lines around them compared to smaller ones. In this regard, the sequencing was effective in terms of the *electric field*, particularly its patterns. As a result, he was allocated a developing (3) score for the logical sequence that showed the 'interrelatedness of concepts.' However, when studying the *electric field strength*, we realized that the sequencing was also meant to explain the vector nature of the electric field at a point by examining the formula $E=F/q$. Jabulani explained that the electric field strength is a vector quantity because it is a quotient of a vector (a force) and a scalar quantity (a charge). We regard this approach of explaining vectors and scalars as abstract for learners. Nevertheless, Jabulani used the pre-concept of electric field patterns to determine directions of electric fields at a point before superimposing them to obtain their resultants. As such, a basic (2) score was allocated because a few concepts were 'developed from or linked with corresponding pre-concepts.'

Knowledge and skills related to learners' understanding of concepts

We observed that Jabulani consistently calculated the magnitudes of *electrostatic forces* and *electric field strengths* before representing them with vector diagrams. It later became evident that this approach was to avoid a potential challenge. The challenge is that learners may associate the strengths of forces and fields with distance only and disregard the effect of the magnitudes of charges. Jabulani uncovered this difficulty in terms of forces and indeed learners believed that the charge closest to the reference charge exerted the strongest force regardless of its magnitude. Hence, he emphasized that the magnitudes of forces must be calculated before they are represented using vector diagrams. Jabulani also instructed learners not to substitute signs of charges into Coulomb's law when calculating *electrostatic forces* and proceeded to exclude them when calculating the *electric field strength*. He stated adequate reasons for excluding the signs of charges, arguing that 'you will be tempted to say … uhm … if you get a negative sign here (a negative force) you will be tempted to say it's going to the left.' Regarding the *electric field strength*, he also addressed the challenge of associating the electric field at a position with a test charge placed at that position (Bohigas & Periago, 2010). This was observed when he said 'the size of this charge q will not affect the magnitude or the strength of the electric field at any point because we use this equation $E = k\frac{Q}{r^2}$. Does this equation have q?' He expanded on this challenge during the interview. He said:

> When they ask them to calculate the electric field of the bigger charge … Instead of using the value for this one (source charge, Q), they use the value of this one (the test charge, q) when they get to this formula $E = k\frac{Q}{r^2}$.

It is documented in the literature that learners often cannot distinguish between the charge that creates an electric field and the charge that tests it (Li & Singh, 2017). As such, Jabulani was allocated a developing (3) score in terms of difficulties associated with the *electrostatic force* and *electric field strength* because he 'addressed some areas of difficulty while expanding on the explanations.'

In contrast, when discussing the *electric field*, Jabulani made a statement that could encourage one of the misconceptions documented in the literature when learners asked if the test charge is always positive. He responded: 'it can be a negative one, but it's better to understand it with a positive one. Just stick to a positive one.' The misconception is that some learners believe that all charges, regardless of polarity spontaneously move in the direction of the electric field (e.g., Bilal & Erol, 2009). Nevertheless, when drawing electric field patterns, he emphasized that field lines must neither touch nor cross, as this is a common challenge documented in the literature (Taskin & Yavas, 2019). Jabulani was therefore allocated a basic (2) score for addressing 'a few areas of learners' difficulties.'

Knowledge and skills related to conceptual teaching strategies including representations

Jabulani's teaching strategies were characterized by questions and explanations while using representations to support concepts. Regarding *electrostatic forces*, Jabulani used subscripts F_1 and F_2 to denote forces on Q_2 were exerted by Q_1 and Q_3 for example. When learners requested that he uses $F_{1 \text{ on } 2}$ and $F_{3 \text{ on } 2}$, he insisted that they use F_1 and F_2 because 'when you get to university it is [labelled] like that.' Furthermore, he did not specify directions of the separate forces. Instead, he described charge interactions, e.g.,' $F_1=1.8\times10^{-8}$ N repulsive' which corresponds with his notation. When superimposing the forces, he then referred to their vector nature and hence represented them using vector diagrams drawn in proportion to their magnitudes after they were calculated. These diagrams ensured that the directions of the resultant forces became evident. Directions were only specified in the resultant force, for example $F_{net}=1.2\times10^{-8}$N left, arguing that:

> Now it is clear that you are talking about one charge there (the reference charge), that's why now you can be able to specify whether it is to the right or to the left instead of attraction here (F_1) and attraction here (F_2).

To emphasize the idea of a resultant force, Jabulani did a tug of war with one of the learners to try and demonstrate the effect of the stronger force on the reference charge. According to the rubric, he was allocated a developing (3) score.

Regarding the *electric field*, Jabulani used a representation when he drew a diagram showing a source charge (+/-*Q*) that creates the electric field, a positive test charge (+*q*) and direction of the force (*F*) acting on the test charge. While referring to the diagram, Jabulani formulated suitable questions for learners to determine the directions of forces acting on the test charge. This discussion explained that electric field lines point away from a positive and towards a negative charge. Having mentioned that a test charge can be negative, he was asked to comment on it. He defended his answer, stating that he does not want to restrict learners to think of a positive test charge only but rather on the principle. This is important in teaching. However, as he explained in his response, when one uses a negative test charge, the direction that they will get is the opposite, which complicates the concept. Based on the observations made, he was allocated a basic (2) score mainly because of the inclusion of a negative test charge.

Regarding the *electric field strength*, the same diagram used to explain directions of electric field lines was used to facilitate the derivation of the formula $E = k\frac{Q}{r^2}$. Questions were once again used to engage learners with the content. For example, when solving problems of field superposition, Jabulani asked learners to indicate the direction of each field at the point of interest. One such question involved two positive source charge, Q_1 and Q_2, and a point of interest where the resultant electric field of the two charges had to be determined. The following dialogue took place:

> Jabulani: If you look at that charge Q_1, at this point [of interest], is the electric field going to point that way or that way (pointing to the left and to the right using his hands)?
>
> Learner A: Sir, to the right because Q_1 is positive and they will repel, because the test charge is also positive.
>
> Jabulani: You are correct by saying because Q_1 is positive, but do not talk about this one [Q_2] (the learner tried to defend his case but was overpowered by the raised tone of the teacher), IGNORE THIS ONE [Q_2]. So, you cannot talk of repulsion and everything. Remember, according to what we've been doing here [electric field patterns], if you are drawing an electric field around a positive charge, it will be pointing away. If Q_1 was negative, it was going to be towards (while drawing a vector to the left) but because it is positive, it is pointing away.

The learner answered based on the idea that underpins the directions of electric fields – the direction of the force acting on a positive test charge. By not allowing the learner to defend her case, Jabulani may have suggested that she was mistaken. Nevertheless, he expanded his strategy used to obtain the directions, by isolating the source charges and drawing their electric field patterns while showing the point of interest. He then focused the attention of learners to the electric field line that passes through the point of interest as it indicates the desired direction of the electric field at that point. Once the directions were determined, Jabulani represented the electric fields using vector diagrams which he reconstructed relative to their magnitudes once they had been calculated. Similar to *electrostatic forces*, Jabulani did not specify the directions of the electric fields at a point in writing, which prompted one learner to ask 'Sir, so direction for E_1 repulsion or away?' to which he responded, 'at this point we are doing calculations so do not worry too much about indicating the direction.' We believe that specifying directions of separate forces and fields makes the connection with the resultants easy to follow. Based on the observations, Jabulani's competence was basic (2) because he 'seldom involved learners in the lesson' as shown in his interaction with learner A.

Case Study 3–Merriam

Knowledge and skills related to curricular saliency

Our observation revealed a noticeable contrast in Merriam's presentation of the big ideas, as well as her explanations of the interrelatedness between concepts. In terms of *electrostatic forces*, Coulomb's law was related with Newton's law of universal gravitation, focusing explicitly on their similarities and differences. Furthermore, she used the pre-concepts of charge interactions to determine directions of electrostatic forces. In addition, problems involving resultant forces in a straight line and in 2D were solved with the application of previously learnt skills, for example the theorem of Pythagoras and trigonometric ratios to determine and represent magnitudes and directions of resultant forces in 2D. As such, a developing (3) score was allocated for 'discussing most of the prescribed ideas' while linking them 'with corresponding pre-concepts.'

In contrast, many aspects of the *electric field* and the *electric field strength* were not discussed. Regarding the *electric field*, Merriam referred learners to the pre-concept of magnetism as recommended in the curriculum. However, she regarded the two fields as being identical, with her opening statement being 'I know we have all seen the electric fields…the field lines around a bar magnet.' We initially believed this was an oversight. However, when listing pre-concepts for the topic of electrostatics during the interview, she included 'charges, a positive and a negative charge around a magnet.' This indicates that she did not distinguish between charges and magnets, a misunderstanding that is documented in the literature (Hekkenberg et al., 2015). Merriam also did not discuss the role of a positive test charge in determining directions of electric field lines; she merely stated that electric field lines point away from a positive charge and towards a negative one. When asked about the exclusion of the positive test charge, she replied:

> We are following the ATP (annual teaching plan) and the work schedule, which guides us what needs to be taught and what should be excluded. So, before we start with electric fields, you already know that learners must know definition of an electric field, learners must know what a test charge is.

In this regard she revealed a restricted understanding of the curriculum which makes it explicit that the concept of electric field is discussed for the first time in grade 11 (DoBE, 2011). Regarding the *electric field strength*, she only solved example problems that involved electric fields set up by isolated charges, using $E=F/q$ or $E = k\frac{Q}{r^2}$. Furthermore, she did not include directions of *electric field strengths* in her calculations, focusing solely on the magnitudes. The idea of field superposition was also not discussed at all, which is seemingly because it demands the directions of electric fields, an idea that Merriam neglected. Based on our observations and the scoring rubric, Merriam was allocated a limited (1) score for both the *electric field* and the *electric field strength*, mostly for not discussing many of the 'ideas that are prescribed in the curriculum.'

Knowledge and skills related to learners' understanding of concepts

We observed that Merriam addressed a single area of difficulty in each big idea although several opportunities for addressing other challenges presented themselves. Regarding *electrostatic forces* and *electric field strengths*, she emphasized that signs of charges must be excluded in calculations because they indicated the polarity of charges. In terms of *electric fields*, she emphasized that electric field lines neither touch nor cross, which is a typical challenge that learners face (Taskin & Yavas, 2019). Regarding missed opportunities, an explicit opportunity emerged when solving problems involving resultant *electrostatic forces* in 2D. Merriam drew the vector diagram showing the resultant force and placed an angle θ at the origin between the resultant and the vertical force. She then asked learners to identify a suitable trigonometric function to calculate the angle. When learners answered incorrectly, she moved θ and placed it between the resultant and the horizontal force to corresponded with the learners' responses. This was an opportunity for her to engage with learners' understanding of trigonometric ratios. She also missed other opportunities to engage with difficult concepts. For example, instead of elaborating on the concept of electric field strength, she simply provided a few statements:

> A strong electric field exert a stronger force than a weak one does. If we know the electric field strength or the intensity, then we can calculate the force on any charge placed in the field … A unit charge is a charge on one coulomb, q Is a charge placed at a point in the field, it is not the source of the field.

These statements could have been clarified to explain the roles of the source and positive test charge and to emphasize that the test charge does not influence the electric field. Merriam was allocated a basic (2) score across the three big ideas for addressing 'a few areas of learners' difficulties.'

Knowledge and skills related to conceptual teaching strategies including representations

When teaching *electrostatic forces*, Merriam formulated suitable questions and provided explanations in various instances. For example, to

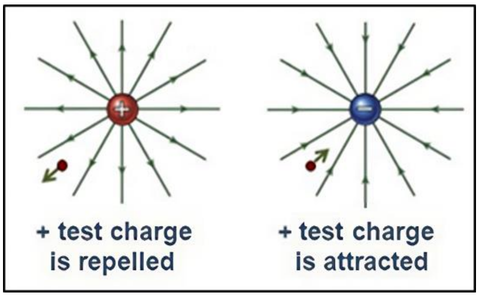

Figure 2. A diagram suitable for the electric field and electric field strength (Broster et al., 2012)

determine directions of electrostatic forces exerted on a charge Q_2 by other charges, Q_1 and Q_3, she asked' … the force between Q_2 and Q_3, is it attraction of repulsion? [learners; attraction]. In which direction will the force face?' Once the directions were determined, she represented the forces using a vector diagram that she labelled adequately and specified the directions in writing, e.g.,'$F_{Q1 \text{ on } Q2}=5\times10^{-5}$N to the left'. However, she also missed opportunities to address learners' challenges, for example in the case described above where she simply changed an angle in a diagram instead of engaging the learners on a conceptual level. Consequently, she was allocated a basic (2) score.

Regarding the *electric field* and the *electric field strength*, Marriam's conceptual teaching strategies were restricted. She read concepts as they are stated in the electronic textbook that she projected on the smart board without pausing for questions, explanations and/or clarifications. She also omitted key aspects of the big ideas, as indicated in the discussion of curricular saliency. For example, while paging through the electronic book, a representation suitable for aspects of the electric field and its strength appeared on the screen (**Figure 2**).

Figure 2 is suitable for explaining the directions of electric field lines using a positive test charge in the big idea of the *electric field* and for deriving the formula for the *electric field strength* at a point, $E = k\frac{Q}{r^2}$. However, she ignored the representation and continued reading. Merriam also displayed a class activity on the screen and instructed learners to omit the first question about a positive test charge and its role in electric fields. Later, learners asked her what was meant by a test charge and to explain the directions of electric fields. She responded to the questions, as follows:

> [Positive test charge]: It's a small charge that is used to determine the magnitude of the charge that is placed there (the source charge). It is used like the controlled variable in an experiment.
>
> [Directions of electric field lines]: Remember an electric field is where your charge placed at one point will move. It's the direction where your charge will move. If I'm placing a negative charge here, and it's a negative charge, they say the electric field goes … meaning the force that the charge is experiencing is towards the negative sign. If it's positive, then the electric field will move that direction (she used her hands to point away depicting the direction of the electric field around a positive charge).

These responses indicate poor understanding of the concepts of an electric field, having referred to 'a small charge' and describing the direction of the electric field as 'where your charge will move.' During the interview, she was asked about her explanation of the direction of an electric field, to which she responded, 'this one requires me to refer again. It's been a while since I moved past electric fields and my mind has forgotten about them. I'm currently busy with chemistry.' This is an indication of a lack of content knowledge. As a consequence of lacking content knowledge, her problem-solving strategy regarding the *electric field strength* promoted algorithms rather than conceptual understanding. She used problems that were given as examples in the textbook, restricting them to isolated charges. Furthermore, she did not draw any diagrams to represent fields. All she did was write the formula, substitute the given quantities to calculate the unknown. Based on these observations, Merriam was allocated a limited (1) score for teaching strategies regarding the *electric field* and the *electric field strength* because they lacked the 'use of representations and focus on important and difficult concepts.'

Case Study 4–Patrick

Knowledge and skills related to curricular saliency

Patrick revisited the concepts of electrostatics that are taught at grade 10 which could serve as prior knowledge for all three big ideas. Regarding *electrostatic forces*, he revisited pre-concepts of forces including the theorem of Pythagoras and trigonometric ratios. He also related Coulomb's law and Newton's law of universal gravitation by outlining their similarities and differences. Furthermore, the pre-concepts of charge interactions were used to determine the directions of forces before they were represented using vector diagrams. As such, a developing (3) score was allocated for 'discussing most of the prescribed ideas' while linking them 'with corresponding pre-concepts.' Regarding *electric fields*, he did not revisit the pre-concept of magnetic fields as prescribed in the curriculum. Nevertheless, he explained directions of electric field lines using the pre-concept of charge interactions. Regarding the electric field strength, Patrick did not show the link between forces and fields beyond just stating the idea of force per unit charge as he did not derive the formula $E = k\frac{Q}{r^2}$. Nevertheless, he determined directions of electric fields at a point using the pre-concept of a positive test charge. Patrick was therefore allocated a basic (2) score for *electric fields* and *electric field strength* because a few concepts were 'developed from or linked with corresponding pre-concepts.'

Knowledge and skills related to learners' understanding of concepts

Generally, Patrick presented concepts without paying attention to challenges. When calculating magnitudes of *electrostatic forces* and *electric field strengths,* he excluded signs of charges. However, the reasons for the exclusion were underspecified, stating that 'when you perform your calculations you omit the negative because it tells us about the direction.' Patrick also emphasized that learners must not confuse Coulomb's law and the formula $E = k\frac{Q}{r^2}$ when calculating magnitudes of forces and fields. These represent 'few areas of learners' difficulties' in *electrostatic forces* and *electric field strength* which resulted in a basic (2) score. In contrast, regarding the *electric field*, Patrick was allocated a limited (1) score because he did not facilitate 'discussions that uncover learners' understanding of concepts and difficulties.'

Knowledge and skills related to conceptual teaching strategies including representations

Patrick's strategies were characterized by questions and explanations while using representations. Generally, he formulated questions that required learners to study charge interactions to determine directions of electrostatic forces and electric fields using a positive test charge. For example, regarding *electrostatic forces*, he asked' … do you agree with me that A will pull B? Remember a force is a pull or a push. Pull is an attraction, right? In which direction does it pull it, left or right?' Regarding the directions of electric fields, he asked' … the direction of the electric field is the direction of the force [on a positive test charge] … what is the nature of the force between this charge [the source charge] and the test charge?' However, his strategies did not pay attention to addressing difficult concepts. Despite excluding signs of charges, he did not explain the reasoning behind, which resulted in the following dialogue in terms of *electrostatic forces*.

> Learner A: Why does not the answer have a negative sign?
>
> Patrick: By the way negative and positive tell us about what?
>
> Learners: Direction.
>
> Patrick: They tell us about the nature of the force, so it means the force is attraction. We have accounted for that negative sign.

Patrick missed an opportunity to rephrase the question, seeing that learners thought of the signs in terms of direction. Once the directions of forces and fields were determined, he represented them using vector diagrams constructed in proportion to the anticipated magnitudes. In this regard, Patrick focused on distance only, disregarding the effect of charge magnitudes. Thus, the *electrostatic force* and the *electric field strength* of the charge closest to the reference charge and point of interest were represented using longer vector diagrams. It is not always the case that the closest charge will have the greater effect, because the size of the charge also counts. Nevertheless, the vectors were labelled adequately, for example $F_{A\ on\ B}$= and $E_{Q1\ on\ P}$. Furthermore, the directions were specified next to their magnitudes and used alongside a reference frame when determining magnitudes and directions of resultant forces and fields. According to the rubric, Patrick was allocated a basic (2) score across the big ideas for using 'representation while explaining a few important and difficult concepts.'

DISCUSSION

RCM allows the possibility that PCK may have a concept specific nature in addition to discipline and topic specific grainsizes (Carlson & Daehler, 2019; Veal & MaKinster, 1999). The results of the present study, summarized in **Table 1**, indicate that the scores allocated for teachers' dynamic PCK indeed varied across the big ideas of electrostatics. The present results therefore support findings of an earlier study that focused on static PCK (Mazibe et al., 2020). In particular, the results suggest that enacted PCK also varies across fundamental concepts of topics, not necessarily electrostatics. Furthermore, they provide empirical evidence that supports the speculation made in the literature about the concept specific nature of PCK.

The variations in PCK appear to be related to the nature of the concepts and teachers' content knowledge in each. Three of the teachers obtained the highest score in the concept of the *electrostatic force*. This may be related to the nature of the concepts, as the *electrostatic force* has a wide base of prior knowledge, including vectors, Newton's laws, gravitational forces as well as repulsion and attraction between charged objects. In contrast, the concepts of *electric fields* and *electric field strength* build on a relatively small body of prior knowledge found in the topics of magnetic field lines and vector addition. The similarity with the gravitational field is not often recognized as the curriculum does not emphasize the field aspect of gravity. Instead, it focuses on gravitational forces which are related to *electrostatic forces*. This variation of the nature and presentation of concepts in the curriculum was also evident in the practice of the teachers. In terms curricular saliency, the teachers predominantly utilized the wide range of pre-concepts associated with *electrostatic forces*. In contrast, little prior knowledge is associated with the field concept, which contributes to a limited conceptual foundation on which to build the concept of *electric fields*. This may explain the poorer PCK scores for the concepts.

Still on the nature of concepts, *electrostatic forces* and *electric field strength* are predominantly quantitative while the *electric field* is a qualitative concept. As such, the presentations of the concepts of forces and field strengths predominantly showed similarities in terms of algorithms. For example, Jabulani and Patrick drew vector diagrams for forces and fields in proportion to their magnitudes. Jabulani constructed the diagrams after calculating their magnitudes while Patrick inferred them from their relationship with distance. Furthermore, while Patrick generally did not pay attention to difficulties across the concepts, the fact that forces and fields had to be calculated prompted him to address the challenge associated with confusing signs of charges with vectors. However, as there are no calculations in the concept of an electric field, challenges were neither uncovered nor addressed.

In terms of teachers' content knowledge, it is documented that electric fields and their strengths are often difficult for learners compared to electric forces (Garza & Zavala, 2013), which was also the case for Merriam. When teachers lack content knowledge, they tend to exhibit negative emotions, for example lack of confidence in terms of teaching the corresponding concepts (Melo et al., 2017; Park & Oliver, 2008). As such, they either exclude the corresponding concepts in their lessons or discuss them superficially by asking lower order questions while promoting algorithms rather than conceptual understanding (Childs & McNicholl, 2007; Rollnick et al., 2008). This can explain why Merriam excluded various aspects of electric fields. Also, due to a lack of content knowledge, Vuyelwa was not able to explain how repulsive and attractive forces amongst two different pairs of charges should be considered in order to determine the direction the resultant force on the central charge.

Although the study did not set out to compare PCK of the participating teachers, the results are intriguing as the pre-service teachers tended to outperform the experienced in-service teachers. Literature points out that PCK develops with experience (e.g., Kind, 2009) while acknowledging content knowledge as its pre-requisite (e.g., Rollnick et al., 2008). The in-service teachers' lower PCK scores could be explained by a combination of factors. For Merriam, the low PCK score can be ascribed to a lack of content knowledge. For Patrick on the other hand, PCK was largely restricted because he focused on the concepts that are examined. Furthermore, both in-service teachers had a strong chemistry background compared to physics according to their qualifications. As electrostatics is a physics topic, the teachers were probably less confident in teaching it. However, these are only speculations and highlight research opportunities for investigating the knowledge and practice of physical sciences teachers with either a physics or chemistry background in various topics of the subject.

CONCLUSIONS

The purpose of the present study was to compare teachers' dynamic PCK across fundamental concepts of electrostatics and to explain any variations. The results of the study have shown variations in the enactment of PCK. The variations appeared to have been related to the nature of the concepts, as well as teachers' content knowledge in each concept. While it is often desirable to describe teachers' overall PCK, the findings highlight the importance of considering variations in smaller grainsizes of PCK. For example, studying PCK at the concept grainsize can reveal teachers' strengths and weaknesses regarding specific concepts, which could serve as guidance in terms of designing pre-service teacher education and in-service teacher professional development approaches. The results have also shown the importance of developing teachers' content knowledge of every single concept that is relevant to the topic of interest following the evidence that when the content knowledge is lacking, PCK needed for teaching the concept gets compromised. Furthermore, when studying PCK in relation to other aspects of teaching and learning, for example teachers' emotions (Melo et al., 2017) and evidence of learning (Mazibe, 2020), it is reasonable to consider specific concepts for a more intimate indication of the relationships. If the concept-specific nature of PCK is to be theorized, then the starting point would be in studying variations in teachers' PCK about big ideas of a topic. This would enable researchers to explore features of PCK that are unique to concepts but not evident at topic level. In terms of future research, Vuyelwa's case has indicated the need to study classroom discourse in relation to how teachers enact PCK across the fundamental concepts of a topic.

We emphasize that these results should be considered with caution given the limitations of the research. While a small sample was necessary to allow for an in-depth analysis of PCK, the results of a case study should not be generalized. Results also show that variations in PCK at concept level already exist at pre-service teacher level. Therefore, teacher training programs should ensure that different concepts within a topic are addressed not only to understand the concepts but also how to transform concepts within a topic for instruction.

Author contributions: All authors have sufficiently contributed to the study and agreed with the results and conclusions.

Funding: The study was funded by the National Research Foundation, Grant number: TTK180411319423

Ethical statement: Authors stated that the ethical clearance was granted by the ethics committee of the University of Pretoria, clearance number: SM 18/04/01.

Declaration of interest: No conflict of interest is declared by authors.

Data sharing statement: Data supporting the findings and conclusions are available upon request from the corresponding author.

REFERENCES

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. https://doi.org/10.1002/tea.21271

Alonzo, A. C., Berry, A., & Nilsson, P. (2019). Unpacking the complexity of science teachers' PCK in action: Enacted and personal PCK. In A. Hume, R. Cooper, & A. Borowski, (Eds.), *Repositioning pedagogical content knowledge in teachers' knowledge for teaching science* (pp. 271-286). Springer. https://doi.org/10.1007/978-981-13-5898-2_12

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. https://doi.org/10.1002/tea.21055

Barendsen, E., & Henze, I. (2019). Relating teacher PCK and teacher practice using classroom observation. *Research in Science Education, 49*(5), 1141-1175. https://doi.org/10.1007/s11165-017-9637-z

Bernardo, R., du Plessis, H., du Plessis, S., Fanoy, C., Jones, E., Lees-Rolfe, P., McDougall, J., Reynecke, K., Schmidt, M., & Smith, L. (2012). *DocScientia grade 11 textbook and workbook* (4th ed).

Bilal, E., & Erol, M. (2009). Investigating students' conceptions of some electricity concepts. *Latin-American Journal of Physics Education, 3*(2), 193-201.

Bohigas, X., & Periago, M. C. (2010). Modelos mentales alternativos de los alumnos de segundo curso de Ingenieriá sobre la ley de Coulomb y el campo eléctrico [*Alternative mental models of second-year engineering students of Coulomb's law and the electric field*]. *Revista Electrónica de Investigación Educativa* [*Electronic Journal of Educational Research*], *12(*1), 1-15.

Broster, P., Horn, W., James., & Solomons, N. (2012). *Oxford successful grade 11 learner's book* (3rd ed).

Carlson, J., & Daehler, K. R. (2019). The refined consensus model of pedagogical content knowledge in science education. In A. Hume, R. Cooper, & A. Boroswki (Eds.), *Repositioning pedagogical content knowledge in teachers' professional knowledge* (pp. 77-92). Springer. https://doi.org/10.1007/978-981-13-5898-2_2

Chan, K. K. H., & Hume, A. (2019). Towards a consensus model: Literature review of how science teachers' pedagogical content knowledge is investigated. In A. Hume, R. Cooper, & A. Borowski (Eds.), *Repositioning PCK in teachers' professional knowledge for teaching science* (pp. 3-76). Springer. https://doi.org/10.1007/978-981-13-5898-2_1

Chan, K. K. H., Rollnick, M., & Gess-Newsome, J. (2019). A grand rubric for measuring science teachers' pedagogical content knowledge. In A. Hume, R. Cooper, & A. Boroswki (Eds.), *Repositioning pedagogical content knowledge in teachers' knowledge for teaching science* (pp. 251-269). Springer. https://doi.org/10.1007/978-981-13-5898-2_11

Childs, A., & McNicholl, J. (2007). Science teachers teaching outside of subject specialism: Challenges, strategies adopted and implications for initial teacher education. *Teacher Development, 11*(1), 1-20. https://doi.org/10.1080/13664530701194538

DoBE. (2011). Curriculum and assessment policy statement: Grade 10-12 physical sciences. *Department of Basic Education*. https://www.education.gov.za/Curriculum/NationalCurriculumStatementsGradesR-12.aspx

Garza, A., & Zavala, G. (2013). Contrasting students' understanding of electric field and electric force. *AIP Conference Proceedings, 1513*(1), 142-145. https://doi.org/10.1063/1.4789672

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-examining pedagogical content knowledge in science education* (pp. 28-42). Routledge.

Grossman, P., Hammerness, K., & McDonald, M. (2009). Redefining teaching, re-imagining teacher education. *Teachers and Teaching: Theory and Practice, 15*(2), 273-289. https://doi.org/10.1080/13540600902875340

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. https://doi.org/10.1080/10288457.2015.1004833

Henze, I., & Barendsen, E. (2019). Unravelling student science teachers' pPCK development and the influence of personal factors using authentic data sources. In A. Hume, R. Cooper, & A. Borowski (Eds.), *Repositioning pedagogical content knowledge in teachers' knowledge for teaching science* (pp. 201-221). Springer. https://doi.org/10.1007/978-981-13-5898-2_9

Kind, V. (2009). Pedagogical content knowledge in science education: Perspectives and potential for progress. *Studies in Science Education, 45*(2), 169-204. https://doi.org/10.1080/03057260903142285

Li, J., & Singh, C. (2017). Investigating and improving introductory physics students' understanding of the electric field and superposition principle. *European Journal of Physics, 38*(5), 055702. https://doi.org/10.1088/1361-6404/aa7618

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. https://doi.org/10.1002/tea.20007

Mavhunga, E., & van der Merwe, D. (2020). Bridging science education's theory-practice divide: A perspective from teacher education through topic-specific PCK. *African Journal of Research in Mathematics, Science and Technology Education, 24*(1), 65-80. https://doi.org/10.1080/18117295.2020.1716496

Mazibe, E. N. (2020). *The relationship between teachers' pedagogical content knowledge about electrostatics and learners' performance* [Doctoral dissertation, University of Pretoria]. http://hdl.handle.net/2263/80475

Mazibe, E. N., Gaigher, E., & Coetzee, C. (2020). Comparing pedagogical content knowledge across fundamental concepts of electrostatics: A case of three pre-service teachers. *African Journal of Research in Mathematics, Science and Technology Education, 24*(2), 143-155. https://doi.org/10.1080/18117295.2020.1765607

Melo, L., Cañada, F., & Mellado, V. (2017). Exploring the emotions in pedagogical content knowledge about the electric field. *International Journal of Science Education, 39*(8), 1025-1044. https://doi.org/10.1080/09500693.2017.1313467

Park, S., & Oliver, J. S. (2008). Revisiting the conceptualization of pedagogical content knowledge (PCK): PCK as a conceptual tool to understand teachers as professionals. *Research in Science Education, 38*(3), 261-284. https://doi.org/10.1007/s11165-007-9049-6

Park, S., Jang, J. Y., Chen, Y. C., & Jung, J. (2011). Is pedagogical content knowledge (PCK) necessary for reformed science teaching?: Evidence from an empirical study. *Research in Science Education, 41*(2), 245-260. https://doi.org/10.1007/s11165-009-9163-8

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. https://doi.org/10.1080/09500690802187025

Shulman, L. S. (1986). Those who understand: Knowledge growth in teaching. *Educational Researcher, 15*(2), 4-14. https://doi.org/10.3102/0013189X015002004

Shulman, L. S. (2015). PCK: Its genesis and exodus. In A. Berry, P. Friedrichsen, & J. Loughran (Eds.), *Re-examining pedagogical content knowledge in science education* (pp. 3-13). Routledge. https://doi.org/10.4324/9781315735665-6

Taskin, T., & Yavas, P. U. (2019). Examining knowledge levels of high school students related to conductors at electrostatic equilibrium and electric field lines using the drawing method. *Research in Science Education, 51*, 577-597. https://doi.org/10.1007/s11165-018-9808-6

Veal, W. R., & MaKinster, J. G. (1999). Pedagogical content knowledge taxonomies. *The Electronic Journal for Research in Science & Mathematics Education, 3*.

APPENDIX A

Table A. The rubric used to assess and quantify enacted PCK in each big idea on a four-point scale

	Limited (1)	Basic (2)	Developing (3)	Exemplary (4)
Curricular saliency	• The teacher does not discuss ideas that are prescribed in the curriculum. • The new concepts are not developed from or linked with corresponding pre-concepts. • The sequencing of concepts is illogical, and the interrelatedness of the concepts is not explained. • The relevance of the concepts is not explicit.	• The teacher discusses only a few ideas prescribed in the curriculum. • A few of the new concepts are developed from or linked with corresponding pre-concepts. • The sequencing of concepts is illogical, and the interrelatedness of concepts is seldom explained. • The relevance of the concepts does not support conceptual understanding.	• The teacher discusses most of the prescribed ideas. • Most of the concepts are developed from or linked with corresponding pre-concepts. • The sequencing of concepts is logical, and the interrelatedness of concepts is often explained. • The relevance of the concepts involve scaffolding towards generic concepts.	• The teacher discusses all ideas prescribed in the curriculum. • The new concepts are developed from or linked with corresponding pre-concepts. • The sequencing of concepts is logical, and the interrelatedness of the concepts is explained. • The relevance of the concepts reveal scaffolding towards specific concepts.
Learners ' understanding of concepts	• No facilitation of discussions that uncover learners' understanding of concepts and difficulties. • The teacher makes no effort to help learners understand difficult concepts.	• Discussions that uncover learners' understanding of concepts and difficulties are seldom facilitated. • A few areas of learners' difficulties are addressed. • The teacher's attempts to explain difficult concepts by providing standardized phrases, e.g., "the field line points away from a positive charge."	• The teacher facilitates cognitive discussions that uncover learners' understanding of some concepts and difficulties. • The teacher addresses some areas of difficulty while expanding on explanations.	• The teacher facilitates cognitive discussions that uncover learners' understanding of concepts and difficulties. • The teacher addresses most areas of difficulty, starting from gatekeeping concepts and expands on explanations.
Conceptual teaching strategies including representations	• Questions are not used to involve learners, making the lessons completely teacher centered. • Explanations are absent. • The strategies support algorithms rather than conceptual understanding. • The strategies lack the use of representations and focus on important and difficult concepts.	• The strategies seldom involve learners in the lesson through questions. • Explanations are seldom provided. • The strategies tend to support algorithms rather than conceptual understanding. • The strategies include the use of a representation while explaining a few important and difficult concepts.	• The strategies sufficiently involve learners in the lesson through questions. • Explanations are sufficiently provided. • The strategies sufficiently support conceptual understanding while encouraging algorithms where necessary. • The strategies include the use of various representations while explaining important and difficult concepts.	• The strategies appropriately involve learners in the lesson through questions. • Explanations are appropriately provided. • The strategies appropriately support conceptual understanding while encouraging algorithms where necessary. • The strategies include the use of various powerful representations while explaining important and difficult concepts.