The relationship between teachers' enacted pedagogical content knowledge and student learning in fundamental concepts of electrostatics

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Abstract

Background: It is commonly understood that teachers' effectiveness is reflected by the performances of their students. On the other hand, teachers' effectiveness is commonly associated with pedagogical content knowledge (PCK).

Purpose: This paper reports a mixed method study exploring the relationship between teachers' PCK and evidence of student learning in fundamental concepts of electrostatics.

Sample: Two in-service and two pre-service teachers as well as 133 students participated in the present study.

Design and methods: Data reflecting teachers' PCK was collected using classroom observations and interviews whereas evidence of student learning was explored using a performance test designed for this research. The PCK and the evidence of student learning were studied in terms of the concepts of electrostatic force, electric field, and electric field strength. The refined consensus model of PCK served as the conceptual framework for the study while the components of the topic-specific PCK model served as the analytical framework. Guided by the components, we developed a rubric to score teachers' PCK on a four-point scale, separately for each concept. Students' performance was also separately averaged for each concept. Quantitatively, correlation coefficients were calculated for each concept. Qualitatively, in-depth analysis of students' test responses in the fundamental concepts was conducted in relation to teachers' engagements with the corresponding concepts.

Results: The results revealed moderate correlations in terms of the concepts of electrostatic force and electric field strength whereas the correlation was weak in terms of the electric field. Furthermore, we found that the test responses of students often matched the way they were taught by their teachers, supporting the quantitative results.

Conclusion: Teachers' PCK and student learning showed weak and moderate correlations that were positive and significant, suggesting that there are other factors beyond PCK that influence student learning.

Keywords: electrostatics, pedagogical content knowledge, science education, student learning

Introduction

It is commonly understood that the effectiveness of teachers is reflected by the performances of their students as they indicate the extent to which the prescribed knowledge has been acquired (Carlson & Daehler et al., 2019). On the other hand, the effectiveness of teachers is commonly associated with pedagogical content knowledge (PCK), originally described by Shulman (1986) as knowledge for transforming content into forms that are understandable to students. It is therefore expected that student performance should be related to teachers' PCK. However, it took several years before researchers started collecting empirical evidence that shows the impact of teachers' PCK on student learning. At the time of the commentary on PCK research studies by Abell (2008), she commented on the paucity of information about the relationship between teachers' PCK and evidence of student learning. In recent times, researchers have started investigating the relationship between teachers' PCK and evidence of student learning, with most studies being quantitative, involving large numbers of teachers and students (e.g., Keller et al., 2017) while others were qualitative in nature and involved smaller numbers of teachers (e.g., Alonzo et al., 2012). Some of the studies found a positive relationship (e.g., Alonzo et al., 2012; Keller et al., 2017), while others reported that there were no links between PCK and student learning (e.g., Gess-Newsome et al., 2019). Chan and Hume (2019) attributed the contrasting findings to the ways in which PCK was conceptualized and operationalized in the investigations. The present study also investigated the relationship between teachers' PCK and evidence of student learning in electrostatics. Differently from previous research, we conducted this study at concept level, focusing on fundamental concepts of electrostatics for a close representation of the relationship between teachers' PCK about different concepts and evidence of student learning in the same concepts. The South African curriculum presents the topic of electrostatics at Grade 11 in terms of three concepts. These are the electrostatic force, electric field, and electric field strength (Department of Basic Education, 2011). As such, we conducted the study focusing on these three concepts.

We selected the topic of electrostatics in view of students' challenges with its concepts as reported in the literature (Maloney et al., 2001). We focused on the PCK enacted during teaching in agreement with Alonzo et al. (2012) to 'capture PCK where it matters most: in its influence on teachers' work with their students' (p. 1216). The research question was formulated as follows: What is the relationship between teachers' enacted PCK and evidence of student learning in fundamental concepts in electrostatics?

Literature review

Research on PCK and student learning

Literature shows that PCK exists as static knowledge stored in the minds of teachers and as enacted knowledge displayed in real classroom situations (Alonzo & Kim, 2016). Various studies have shown that teachers' static PCK does not automatically get translated into enacted PCK because of multiple factors that are presented by the unpredictable nature of lesson progressions, for example unexpected questions from students (e.g., Barendsen & Henze, 2019). Nevertheless, some researchers focused on static PCK and found it to be positively correlated to student learning without observing the enactment of the PCK in real classroom settings (e.g., Kanter & Konstanthopoulos, 2010). Other researchers investigated indirect links between static PCK and student learning by exploring the influence of the PCK on instructional features that are conducive for effective learning (e.g., Ergonenc et al. 2014). The instructional features were studied in terms of cognitive activation (Keller et al., 2017), level of inquiry approaches used when teaching (Gess-Newsome et al., 2019), and the interconnectedness of the content structure of the lesson (Liepertz & Borowski, 2019). Keller et al. (2017) reported that PCK predicted teachers' cognitive activation of students in terms of the task and questions used to facilitate learning in physics education focusing on electricity, energy, and electrical energy. They also reported that cognitive activation predicted student learning (Keller et al., 2017). The influence of PCK on teachers' cognitive activation was also pronounced in the topic of electric circuits by Ergonenc et al. (2014), but they did not find links between cognitive activation and student learning. Instead, as argued by Ergonenc et al. (2014) to explain the discrepancy, student learning was impacted by other instructional characteristics other than just cognitive activation. In the studies by Gess-Newsome et al. (2019) and Liepertz and Borowski (2019), it was reported that static PCK revealed weak relationships with classroom instructions. Furthermore, Gess-Newsome et al. (2019) reported a weak relationship between teachers' PCK and student learning in biology topics whereas the relationship was slightly negative in the study by Liepertz and Borowski (2019) on the force concept.

Other researchers considered classroom practice as the location of PCK and investigated its relationship with student learning. Akinyemi and Mavhunga (2021) studied pre-service teachers' PCK in terms of teaching segments that showed the interactive use of two of more components of PCK which they termed episodes. The researchers reported a positive relationship between the level of proficiency in the interactions of PCK components and the learning gains of students. Alonzo et al. (2012) on the other hand explored teachers' enacted PCK in terms of how they used the content of the topic of optics in their interactions with their students. They concluded that adequate use of content during teaching, characterized by flexibility, richness, and student centredness influenced student learning positively (Alonzo et al., 2012).

Students' challenges in the topic of Electrostatics

Research has shown that electrostatics is challenging for students in the fundamental concepts chosen for this research (e.g., Li & Singh, 2017). Regarding the *electrostatic force*, some students tend to misunderstand the inverse square relationship between force and distance (Maloney et al., 2001). For example, when the distance between two charged objects doubles, they tend to think that the force halves. The application of Newton's third law is also problematic, whereby some students think unequal charges exert unequal forces on each other in proportion to the magnitudes of the charges (Maloney et al., 2001). Furthermore, some students tend to substitute signs of charges into Coulomb's law which they confuse with vector characteristics in terms of direction of the calculated force (Huynh & Sayre, 2018). Regarding the *electric field*, some students associate an electric field existing at a point with any charge that may be placed at that point, particularly a positive test charge (Li & Singh, 2017) such that when the charge is removed, the electric field is believed to disappear (Bohigas & Periago, 2010). Also, students often attach reality to electric field lines (Törnkvist et al., 1993) by regarding them as the means of transmission of electrostatic forces between charged objects (Pocovi & Finley, 2002). Furthermore, some believe that an electric field only exists on the field lines and not in between (Bilal & Erol, 2009). In terms of the *electric field strength*, some students think that the magnitude of the electric field remains constant on a field line, and do not interpret the density of field lines as an indication of field strength (Törnkvist et al., 1993). Students also tend to think that the electric field at a point and the electrostatic force acting on a charge placed at that point are always in the same direction (Furio & Guisasola, 1998). Thus, they believe that all charges spontaneously move in the direction of the electric field regardless of polarity, otherwise charges that move in the opposite direction slow down to a stop (Bilal & Erol, 2009). Regarding the resultant electric field at a point, students believe that fields from like charges always add up at any given point whereas those from unlike charges always subtract (Li & Singh, 2017).

Theoretical background

Ever since the inception of the PCK construct, there has been an implicit assumption that it enhances student learning, However, early PCK models did not explicitly include the possible influence of PCK on student outcomes. The possible influence of PCK on student learning was described recently in the consensus model (Gess-Newsome, 2015) which was later revised to produce the refined consensus model (RCM) (Carlson & Daehler et al., 2019). The present study adopted the RCM for various reasons. Firstly, it describes the construct in terms of three realms, namely, collective PCK (cPCK), personal PCK (pPCK) and enacted PCK (ePCK). Briefly, cPCK refers to knowledge for teaching a specific discipline, topic, or concept that is held by multiple educators (Carlson & Daehler et al., 2019). While cPCK describes common knowledge and skills, pPCK and ePCK are unique and personal to a teacher, with the former being a reservoir of knowledge and skill and the latter being the enacted PCK displayed during actual teaching (Carlson & Daehler et al., 2019). The present study is conceptualized within the realm of ePCK given its direct impact on student outcomes (Carlson & Daehler et al., 2019).

The RCM also recognizes the grainsizes of PCK, including the concept specific level in addition to the discipline and topic specific grainsizes (Veal & MaKinster, 1999). In older literature, PCK was described in terms of the subject, domain and topic-specific grainsizes (Veal & MaKinster, 1999). Respectively, these grainsizes describe knowledge for teaching a subject, a domain, and a topic, for example science, physics, and electrostatics. In recent times, researchers have proposed that PCK also exhibits concept specific features (e.g., Carlson & Daehler et al., 2019). However, the concept specific nature of PCK is yet to be theorized and thus how it differs from the topic specific grainsize is still hazy, particularly because the two are inextricably linked. Nevertheless, the concept specific nature of PCK has been implied in the older literature as researchers investigated PCK at topic level by focusing on fundamental concepts within topics, commonly known as big ideas (Loughran et al., 2004).

In order to characterize the PCK of the teachers, we adopted the five components of the topic specific PCK model by Mavhunga and Rollnick (2013). Despite being developed to suit specific topics, we argue that the components can also describe PCK about specific concepts within topics. The components are *student prior knowledge, curricular saliency, what is difficult to teach, representations including analogies* and *conceptual teaching strategies*. In the literature, the component of *curricular saliency* focuses on the understanding of the curriculum, that is, the sequencing, interrelatedness, and importance of concepts in the topic and/or subject (Mavhunga & Rollnick, 2013). Because the current study was conducted at concept level rather than topic level, we studied *curricular saliency* in terms of understanding the place of the concept in the curriculum, how the concept is interrelated to other concepts, and the importance of the concept within a topic and/or subject. This description includes the links that teachers made between the relevant concept to previously taught concepts. The component of *conceptual teaching strategies* refers to the integration of the other PCK components through discourse such as questions and explanations to produce classroom instructions for teaching important concepts as well as addressing misconceptions and difficulties associated with the concept (Mavhunga & Rollnick, 2013).

Methodology

This study followed a mixed method research approach (Creswell, 2014) dominated by qualitative research to allow for an in-depth interpretation of teachers' PCK in relation to the evidence of student learning in fundamental concepts of electrostatics.

Sample

We invited two pre-service and two in-service teachers to participate in the present study using convenience and purposive sampling. The selection of the participants was informed by reports that PCK develops with experience, with novice teachers often exhibiting lower PCK levels compared to their experienced counterparts (e.g., Kind, 2009). We expected that the sample would include PCK levels ranging from low to high. The biographical information of the selected teachers is summarized in Table 1.

Table 1. Biographical information of the participants.

Pseudonym	Highest qualification	School's resources	Teaching experience (years)	Number of lessons observed	Period per lesson (minutes)	Time spent on electrostatic force (minutes)	Time spent on electric field (minutes)	Time spent on electric field strength (minutes)
Vuyelwa	Final year BEd student	Adequate	N/A	5	40	100	30	60
Jabulani	Final year BEd student	Poor	N/A	4	35	70	20	50
Merriam	Diploma: Analytical chemistry and PGCE	Poor	5	3	30	60	10	20
Patrick	BSc Hons (Chemistry) and PGCE	Poor	10	5	30	75	25	50

Apart from the four teachers, the sample also included a total of 133 of their students. The student sample was adequate to measure student performance quantitatively, while the small number of teachers was desirable for qualitative, in-depth investigation of their PCK.

Data collection

We collected data reflecting PCK enacted during teaching using classroom observations given its direct impact on students (Alonzo et al., 2012). We observed and video recorded all the lessons taught by each of the four teachers on electrostatics to sufficiently characterize their PCK in terms of the concepts of the topic. The number of lesson observations varied across the teachers, depending on the lengths of teaching periods in the different schools as well as the pace of the teachers as shown in Table 1. Segments of the lessons that showed PCK components in teachers' engagements with the content and interactions with students were transcribed for analysis. For triangulation and clarity, interviews were conducted with the teachers after they had presented their lessons focusing on aspects of the lessons that were of interest in the analysis, chosen by the first author. The interviews also explored underlying reasons for teachers' instructional decisions. The interview questions were case specific and were developed based on the observations made in the lesson in relation to specific components of PCK. In the presentation of the results, aspects of the lessons that were revisited during interviews together with teachers' responses are used to supplement data from the observations.

Evidence of student learning was explored using a performance test designed for the purpose of this research. A total of 20 questions were formulated, with each question exploring students' understanding in one of the three fundamental concepts of electrostatics. Some questions are described in the discussion of the results. The complete test can be accessed from Mazibe (2020). The formulation of the questions was informed by the cognitive levels recommended in the South African national examination guidelines (Department of Basic Education, 2011). Most of the questions were adapted from previous national examinations while others were from taken literature in the topic of electrostatics (e.g., Maloney et al., 2001). We used previous national examination question papers as they offer a standard for interpreting our own findings. The test was set by the first author. The content validity of the test was checked by the second and third authors before it was piloted with a group of students who did not participate in the study. Guided by the responses of the pilot group, revisions were made where necessary before the final test was administered to the participating students. In particular, the results of the pilot study suggested revising some of the questions by asking students to provide reasons for some of their answers.

Data analysis

Data from the observations of the lessons and interviews were interpreted deductively using a rubric which was developed by the first author by adapting pre-existing rubrics (e.g., Park et al., 2011). Four scoring levels were developed by identifying indicators of the quality of enactment of teachers' practice in the components of PCK in four categories. The levels were used as Limited (1), Basic (2), Developing (3) and Exemplary (4). The rubric can be found in the supplementary material that accompanies this article. Briefly, the levels indicate instances where none, some, most, and nearly all the aspects of PCK related to a particular component are evident, respectively. For example, if the teacher did not revisit students' *prior knowledge* and subsequently missed opportunities to address gaps and challenges, a Limited (1) score would be allocated for this component. In contrast, an Exemplary (4) score would be allocated if the teacher used a variety of *representations* for the purpose of supporting the explanations of concepts for conceptual development and change. For expert validation, the rubric was examined by the second and third authors of this manuscript to ensure that it adequately describes competence across the four levels for each PCK component. Evidence of teachers' enactment of the PCK components was sought throughout their presentation of each fundamental concept of electrostatics. The evidence could therefore emerge from various segments within the discussion of a fundamental concept. As such, the allocated scores reflected our overall impression about the enactment of a particular PCK component in each of the fundamental concepts. The bulk of scoring was done by the first author and confirmed by the second and third authors. To enhance trustworthiness, we discussed discrepancies from our overall impressions in terms of the enactments of the PCK components to reach agreement about the allocated scores. Thereafter, each teacher's scores for each of the five PCK components were averaged to obtain a single numerical score reflecting the enacted PCK per concept.

The tests written by the 133 students were scored by the first author using a memorandum and moderated by the second and third authors. Scores from the questions that targeted the same concepts were averaged to obtain a single score that represents the performance in that concept. Each student's overall score for each fundamental concept was paired with their teachers' average PCK score for that concept, creating 133 data points per concept. Pearson's correlation coefficient was calculated separately for each concept to investigate possible relationships. To further explore the possibility of relationships, students' responses were compared to their teachers' explanations during lessons using an in-depth qualitative analysis.

Results

The average scores for teachers' enacted PCK and the average test performances of their students are summarised per concept in Table 2.

Table 2. Summary of teachers' PCK scores, students' performance ($n = 133$) and their correlations for three concepts of electrostatics.

	Electrostatic force		Electric field		Electric field strength	
Teacher	PCK score (1–4)	Student performance (%)	PCK score (1–4)	Student performance (%)	PCK score (1–4)	Student performance (%)
Vuyelwa	2.4	61.9	2.2	60.9	3.0	45.3
Jabulani	2.4	49.8	2.2	59.1	2.5	32.8
Merriam	2.0	26.5	1.2	42.5	1.25	13.4
Patrick	2.8	57.1	1.6	52.1	2.25	36.3

Correlation coefficient and P-value.
$r = 0.40$, $P < 0.05$.
$r = 0.30$, $P < 0.05$.
$r = 0.44$, $P < 0.05$.

We found correlation coefficients of 0.40, 0.30, and 0.44 respectively for the fundamental concepts of *electrostatic force*, *electric field*, and *electric field strength*. All the correlations were significant with $P < 0.05$.

We described the strengths of correlations by referring to Schober et al. (2018) as follows; negligible (0.00 to 0.09), weak (0.10 to 0.39), moderate (0.40 to 0.69), strong (0.70 to 0.89) and very strong (0.90 to 1.00). From our data, correlations were moderate for the concepts of *electrostatic forces* and *electric field strength*, but weak for the *electric field* concept.

Qualitative results are discussed below, per fundamental concept. We selected two teachers as illustrative examples for each concept in a form of a vignette to demonstrate the relationship between PCK and student learning. Quotes from the rubric are included to illustrate the allocation of scores in the components that we selected as examples. Scores for all components can be found in Author (2020). In the discussion of student learning in relation to teachers' PCK, we also selected certain questions that focused on the corresponding fundamental concept.

First concept: Electrostatic force

For this concept, we selected Jabulani and Patrick's cases to illustrate PCK and student learning. As shown in Table 1, Patrick enacted better overall PCK compared to Jabulani. Patrick's students also performed better than the students that were taught by Jabulani.

The PCK of the teachers

Due to space constraints, we will only illustrate the *conceptual teaching strategies* used by the teachers when solving problems involving three charges in a straight line and calculating the resultant electrostatic force acting on the charge in the centre. We focus on these problems not only because they involve various aspects of electrostatic force, but also because we tested students on their ability to determine resultant electrostatic forces. In their problem solving approaches, both teachers represented the electrostatic forces acting on the reference charge using vector diagrams drawn in proportion to the magnitudes of the forces. Although the vector diagrams indicated the directions of the forces, Jabulani did not write them in terms of a reference frame. Instead, he used charge interactions, e.g., '$F_1 = 1.8 \times 10^{-8}$N repulsive' while Patrick specified directions such as '$F_{A \text{ on } B}$ = 62.5 N to the left.' Nevertheless, when superimposing the forces acting on the reference charge, Jabulani guided learners to think of negative and positive as shown in the dialogue below:

> Jabulani: How do I know which one will be negative and which one will be positive?
>
> Student A: If the force is to the left, it means it is negative, and if it is to the right, it means it is positive.
>
> Jabulani: That's wrong. You have to compare the two forces, you can see that F_1 is larger than F_2, therefore F_1 will have a negative sign.
>
> Student B: Okay, what if the larger one is to the right?
>
> Student C: But Sir, you said we should look at the magnitude of the forces… [Jabulani interrupted]
>
> Jabulani: We said two things, you can look at the magnitude and the direction as well. If you are looking at the magnitude, it doesn't matter I can still make this one (the force to the right) a

negative. You will still get the same answer, but it will be positive here (the net force). So, whatever you are comfortable with, looking at the direction or you look at the size of the vectors. But the direction is best to look at it because you are used to direction from Grade 10. You know that if it goes to the right, it is positive, and if it goes to the left, it is negative.

We believe Jabulani's approach made it difficult to understand how resultant forces are obtained by not specifying directions of forces in terms of a fixed reference frame. He firstly referred to charge interactions, and then considered the weaker force as negative without completing the argument to translate the negative and positive directions using a fixed frame of reference. Differently, Patrick not only specified the directions of the forces, he also allowed students flexibility in terms of choosing a frame of reference to obtain their resultants as shown in the discussion below:

Student: Meneer (Sir), $F_{A\ on\ B}$ is to the left, it should be minus. (Other students responded, telling the student that the mathematical expression for calculating the resultant is fine the way it is).

Patrick: Leave him alone (addressing the other students). We can also write it in this way; we can say $F_{C\ on\ B} + (- F_{A\ on\ B})$. He wants it in this order because he refers to the Cartesian plane where right, most of the time means positive and left means negative. So, he wants to organise his thinking along those lines, so let's leave him, that's how he will get it right. Ultimately, we will get the same answer.

Based on these observations, we allocated a Developing (3) score for Patrick in terms of *conceptual teaching strategies* for facilitating 'discussions that promote conceptual development' whereas the score was Basic (2) for Jabulani as 'some concepts were explained inadequately'.

The performance of the students

The diagram in Figure 1 was taken from a test item that we selected to illustrate correspondence between teachers' PCK and student learning. The question that we selected required students to determine the forces exerted on sphere B by sphere A and C, and then to find the resultant force.

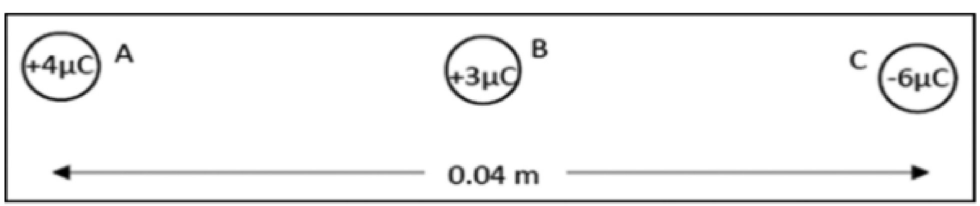

Figure 1. One of the diagrams used to test student performances in electrostatic forces.

We noticed that most of the students solved the problems similar to the way their teachers did and that most of them correctly determined the separate forces acting on the reference charge. Regarding the indications of directions of the separate forces, we allocated full marks regardless of whether they used a reference frame or if they described charge interactions as shown for both solutions in Figure 2. Many of Patrick's students had indicated directions of the separate forces using 'left' and 'right' in the preceding questions, enabling them to determine the resultant force.

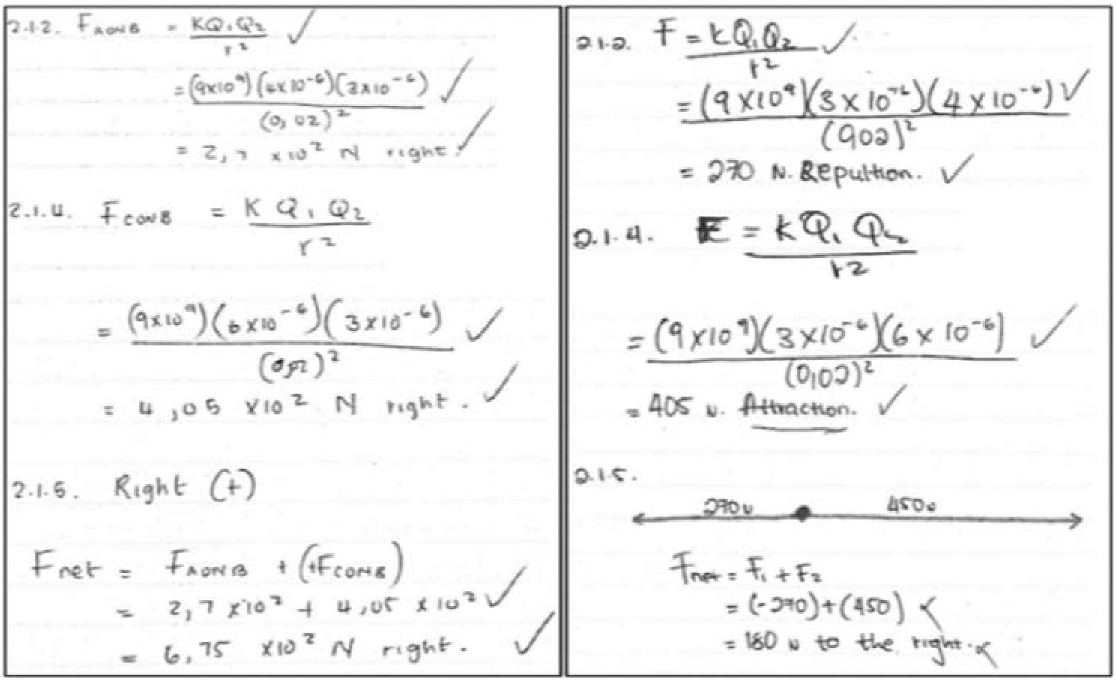

Figure 2. The answers of students taught by Patrick (left) and by Jabulani (right).

Jabulani's students who mostly described the interactions did not realize that even though one of the forces on B was attractive and the other repulsive, they were both to the right due to the arrangement of the charges. These students often regarded attraction and repulsion as opposite directions; hence they subtracted the forces when calculating the resultant. We ascribe this confusion to Jabulani's use of 'attraction' and 'repulsion' in his teaching and his unclear discussion on how to translate these interactions to a reference frame. In this regard, the advantage that Patrick's students had can be tied to the decision of their teacher to specify the directions of the forces in terms of a reference frame. This example shows that the better performance of Patrick's students can be ascribed to the higher level of their teacher's PCK.

Second concept: Electric field

For this concept, we compared Jabulani and Merriam's cases. As shown in Table 1, Jabulani enacted better overall PCK than Merriam. Furthermore, the average performance of his students was also better.

The PCK of the teachers

We observed that Merriam's instruction was informed by an electronic textbook that she displayed on a smart board in front of her class. She revisited the prior knowledge of magnetism as a foundation for electric fields as it was stated in the textbook. However, she was uncertain of the distinction between them, making statements such as 'I know we have all seen the electric fields…the field lines around a bar magnet.' We thought this was an oversight until she mentioned during the interview that grade 10 students 'deal with charges, a positive and a negative charge around a magnet.' This highlighted a gap in her content knowledge which restricted her to effectively use of magnetic fields as an introduction to electric fields. We observed during the lesson that Merriam did not involve the idea of a positive test charge to explain directions of electric field lines. Instead, she simply told students that electric field lines point away from a positive charge and towards a negative charge. A suitable *representation* in a form of a diagram that illustrates directions of fields lines appeared on the smartboard as she was paging through the electronic textbook (See diagram on the right of Figure 3). This was an opportunity to explain directions of field lines using a positive test charge. However, Merriam ignored the diagram and continued with the lesson.

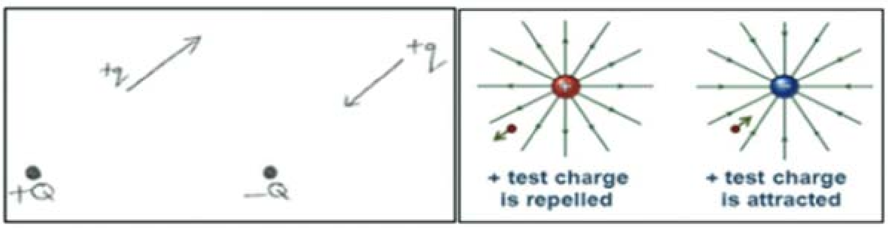

Figure 3. Diagrams drawn and used by Jabulani (left) and diagrams on the smartboard that Merriam ignored (right) when teaching the electric field.

During the interview, she was asked why she did not discuss the positive test charge in her lesson. She responded as follows:

> We are following the ATP (Annual teaching plan[1]) 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 students must know definition of an electric field, students must know what a test charge is.

In this response she misquoted the curriculum which explicitly scheduled electric fields for grade 11 (Department of Basic Education, 2011). Overall, she gave an inadequate presentation of the concept of an electric field. As such, a Limited (1) score was allocated for *curricular saliency* because she did not 'discuss some ideas that are prescribed in the curriculum', as stated in the rubric. Doing so, she denied students an opportunity to learn about the crucial role of a positive test charge in understanding the concept of an electric field.

Jabulani used the prior knowledge of charge interactions alongside a suitable representation to formulate *conceptual teaching strategies* to explain directions of electric field lines. Using a positive test charge (refer to the diagram on the left of Figure 3), he explained:

[1] An annual teaching plan is a document laid out by the Department of Basic Education which outlines key concepts and skills to be taught during a school year. The annual teaching plans can be accessed from https://www.education.gov.za/2021ATPs.aspx

> Jabulani: If I'm bringing the [positive test] charge closer to this positive charge here [+Q], what will happen when they get closer to each other?"
>
> Students: They will repel.
>
> Jabulani: Meaning that the [positive test] charge will move to what direction?"
>
> Students: Away.
>
> Jabulani: The direction in which this charge moves when you place it there, that's the direction of the electric field. If this charge moves away, it means the electric field around this charge is away.

This is an example of a Developing (3) score for *conceptual teaching strategies* following that Jabulani formulated suitable explanations supported by representations to explain directions of electric field lines.

The performance of the students

One of the questions chosen to illustrate the link between PCK and students' answers was based on the diagram in Figure 4. Students were requested to indicate the direction of the electric field at point B.

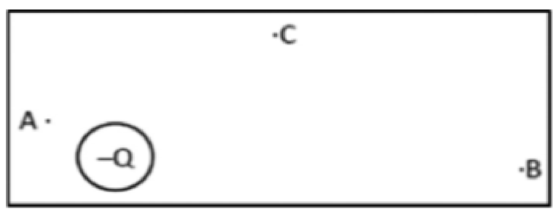

Figure 4. The diagram used in the test questions about electric fields.

Most of Jabulani's students understood that the electric field at B was towards the left. On the other hand, some of Merriam's students indicated that the direction was downwards, showing very little understanding of the concept of an electric field, in accordance with her poor explanation of the concept. The students were also tested on their ability to draw the electric field patterns for a combination of two unlike charges. Misunderstandings included errors in the curves and directions of the electric field lines, with some students drawing vector diagrams instead of field patterns. Such errors were more evident among Merriam's students. The results suggest that Jabulani's discussion of the direction of the electric field lines using a positive test charge promoted better student learning compared to Merriam who did not refer to a positive test charge.

Third concept: Electric field strength

In terms of the electric field strength, we selected Vuyelwa and Patrick's cases as illustrative examples. As shown in Table 1, Vuyelwa enacted better overall PCK compared to Patrick, with her students also performing better.

The PCK of the teachers

In their explanations of electric field strength, both teachers alerted students to challenges to prevent some of the documented *difficulties*. Patrick instructed students not to confuse the formula $E = k\frac{Q}{r^2}$ with $F = k\frac{Q_1Q_2}{r^2}$ and not to substitute signs of charges when calculating electric fields. This is a Basic (2) score for the component of *difficulties* because he addressed a 'few areas of student difficulties' as indicated in the rubric. Vuyelwa on the other hand addressed major challenges documented in the literature, for example the fact that students tend to associate the electric field at a specific point with any charge placed at that point (e.g., Bohigas & Periago, 2010). Hence, she emphasised that the magnitude of the test charge at a point does not affect the magnitude of the electric field strength at that point. She said:

> To determine the electric field around this [source] charge, we use what we call a positive test charge. It is very, very small and is always positive. This test charge (q) does not interrupt the electric field of this charge (Q).

She also explained the role of a source charge Q and the test charge q as well as how they are used to calculate the magnitude of the electric field respectively in the formulae $E = F/q$ and $E = k\frac{Q}{r^2}$. Hence, she was allocated a Developing (3) score for *difficulties* because she addressed 'some areas of difficulty while expanding on the explanations' as stated in the rubric.

In terms of *conceptual teaching strategies*, our focus was on the teachers' problem-solving approaches involving resultant fields of two charges in a straight line shown in Figure 5. To determine the directions of the electric fields created by each point charge at specified locations, Vuyelwa started by using the directions of electric fields, i.e., away from a positive charge and towards a negative charge. Then, she instructed students to imagine a positive test charge placed at the point of interest and to study its interaction with the source charge to obtain the directions of the electric fields. However, her question used to facilitate the discussion was inadequate. She asked:

> We are looking for the direction using this (point X on the screen) as the reference. Using this [point X] as a positive charge. This due to this one, the electric field will go to the…?

Students were unable to respond as the question was unclear which prompted Vuyelwa to revise the strategy as will be shown later. Patrick used the same approach when he drew the positive charge at the point of interest as shown in Figure 5 while facilitating the following discussion:

> Patrick: Remember P will be a positive test charge (while placing + next to P on the right of Figure 5). When I'm looking for the electric field at P as a result of Q_1 and Q_2, can you see that Q_1 will repel P?
>
> Students: Yes.
>
> Patrick: The direction of the electric field is the direction of the force. Q_1 will push P. What will happen with Q_2?
>
> Students: It will attract.

Patrick: The formula that we use is $E = k\frac{Q}{r^2}$. Do not confuse this formula with the formula for F $[F = k\ \frac{Q_1Q_2}{r^2}]$.

Because Vuyelwa's strategy of using a positive test charge did not work, she used a different approach. She added electric field patterns to the diagram and asked students to consider the field line that passes through point X, shown in figure 5. Through this approach, she was able to explain the directions of the electric fields. Once the directions were obtained, both teachers specified them in writing next to the magnitudes of the fields using a fixed reference frame, e.g., '$E_{P,X} = 2.13 \times 10^4\ N.C^{-1}$ to the right' for Vuyelwa and '$E_{Q\ at\ P} = 5000\ N.C^{-1}$ left' for Patrick. The teachers also adequately superimposed the fields to obtain their resultants.

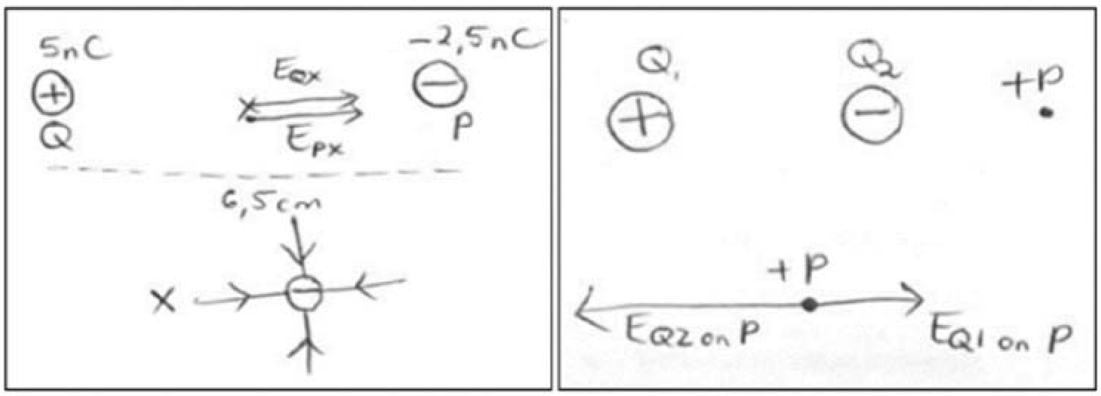

Figure 5. Diagrams used by Vuyelwa (left) and Patrick (right) when solving problems involving the electric field strength.

In terms of the scoring, we allocated Vuyelwa a Developing (3) score for using multiple *conceptual teaching strategies* to 'facilitate discussions that promote conceptual change and development' whereas Patrick was allocated a Basic (2) score for using one approach to 'facilitate discussions that promote conceptual development' only.

The performance of the students

The diagram in Figure 4 was also used in the test to explore students' performance in some aspects of the electric field strength. The following question was asked:

A negative point charge of magnitude -2×10^{-16} C is now placed at point B which is 3 mm to the right of the sphere. At that point, the point charge experiences a force of 4×10^{-15}N. Determine the magnitude of the electric field at point B.

The performance of the students was generally low in both classes. Many students revealed a misunderstanding of the roles of charges, having considered the negative point charge as the source of the electric field (Bohigas & Periago, 2010). Nevertheless, Vuyelwa's students outperformed Patrick's students by 10 percentage points in this problem. We ascribe the better performance of Vuyelwa's students to her emphasis on the roles of the source charge and test charge, as described above for students' *difficulties*.

The diagram in Figure 6 was used to test students' abilities to determine the electric fields set up by sphere P and Q at point X, as well as the resultants of the fields.

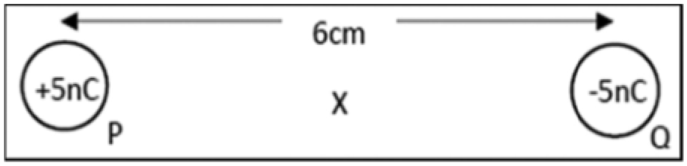

Figure 6. One of the diagrams used to test student performances in the electric field strength.

Again, Vuyelwa's students performed better than Patrick's, which we ascribed Vuyelwa's use of various approaches as shown in *conceptual teaching strategies*. We believe that the various approaches were beneficial for her students, affording them options to determine directions of fields at a point by referring to standard directions of fields, a positive test charge or drawings of electric field patterns. However, obtaining the direction of the resultant field remained difficult for both classes. This was despite the fact that both teachers explained the principle of superposition within a frame of reference to obtain the resultants. In the test, students were requested to write down the magnitude of the resultant electric field strength at point X and to give reasons for their answers. In this example the two field are in the same direction. However, many students believed that since the electric fields at point X were set up by opposite charges, they had to be in opposite directions. As such, they subtracted the two fields instead of adding them. The following reasons were provided by student A (taught by Vuyelwa) and student B (taught by Patrick) for subtracting the fields:

> Student A: They [the electric fields] wouldn't have cancelled because they [charges] are both positive. They [the electric fields] go in the same direction.

> Student B: If both charges are positive, they add, if they are both negative, they also add and maintain the same direction, and if it is negative and positive, they subtract.

These reasons reflect a challenge that is documented in the literature where students believe that the electric fields of like charges always add up while they cancel out if the charges are opposites (Li & Singh, 2017). These examples illustrate how Vuyelwa's and Patrick's students' answers mirrored their teachers' PCK. However, the students' responses revealed that some aspects of the electric field remained difficult for students despite the efforts of teachers.

Discussion and concluding remarks

Earlier, we indicated that we selected a sample of two pre-service and two in-service teachers, expecting to have a wide range of PCK levels. Our expectation, influenced by literature was that the in-service teachers would display higher levels of PCK compared to the inexperienced pre-service teachers (Kind, 2009). The results show otherwise as the pre-service teachers predominantly displayed higher PCK levels than the in-service teachers. We have made speculations to explain this unexpected finding. Firstly, the pre-service teachers had some training in PCK, though not specifically for electrostatics in their teacher education institution.

We believe that the PCK acquired from the training may have been transferred to electrostatics following research findings on the transferability of learned PCK across topics (Mavhunga et al., 2016). Secondly, although the in-service teachers had a stronger chemistry background from their first qualifications, their physics background may have been weaker, making it more challenging for them to teach difficult physics topics such as electrostatics. Merriam's case provided evidence which supports our second speculation where her restricted content knowledge associated with the *electric field* which resulted in poor PCK. In the PCK literature, it is commonly reported that poor content knowledge results in poor PCK (e.g., Rollnick et al., 2008).

Now we turn our attention to the correlations between teachers' PCK and evidence of student learning. Previous literature has reported correlations that were positive (e.g., Akinyemi & Mavhunga, 2021), negative (Liepertz & Borowski, 2019), and negligible (Gess-Newsome et al., 2019). Differently from previous research, we investigated the relationship focusing on three fundamental concepts, with each revealing a different correlation. We found that the concepts of the *electrostatic force* and the *electric field strength,* showed positive and moderate correlations whereas the correlation was weak in terms of the *electric field*. We expected to find stronger correlations and speculate the results can be understood in terms of the challenge to measure PCK accurately. We therefore recommend further research into the conceptualization and measuring PCK, particularly the components that have a greater influence on student learning.

The fact that we did not find strong correlations also supports the notion that while PCK is important as a predictor and/or an indicator of effective classroom instruction, there are other factors that affect student learning (e.g., Gess-Newsome, 2015). We did not investigate such factors and we believe this could be an area for further research in the context of a specific science topic. However, we found that the nature of the fundamental concepts and their distinctive features seemingly influenced the enacted PCK of the teachers and the evidence of student learning. The correlations were stronger for the quantitative concepts of the electric force and electric field strength as compared to the qualitative concept of the electric field. We believe this may be ascribed to the fact that the concepts *electrostatic force* and the *electric field strength* are predominantly quantitative, focusing on determining magnitudes and directions of forces and fields. The teachers spent much time on teaching the techniques of solving the problems, and the responses of the students resembled the problem-solving approaches that their teachers used. Regarding the weak correlation in terms of the *electric field*, we noticed that the teachers did not spend extensive time on the concept, probably regarding it as relatively easy to understand for students, thus scoring low on their PCK. We argue that the students were therefore not influenced much by their teachers but by the nature of the concept, leading to a weaker correlation in the concept.

However, the concept of the electric field strength revealed that some aspects of the concept remained challenging for many students despite the efforts of their teachers. These included understanding the role of a source and a test charge in the formulae $E = k\frac{Q}{r^2}$ and $E = F/q$, a challenge that is documented in the literature (Bohigas & Periago, 2010). Furthermore, understanding the resultant electric field strength at a point of interest was also challenging, which is also another challenge that is documented in the literature (Li & Singh, 2017). This exception can be explained by literature on the extent of difficulties of concepts of the same topic, with the *electric field strength* proving to be inherently challenging for students compared to *electrostatic forces* even after formal instruction (e.g., Garza & Zavala, 2013).

In conclusion, our findings point to variations in the correlation between teachers' PCK and evidence of student learning across concepts of electrostatics, which we ascribed to the nature of the concepts. We acknowledge limitations in the study such as a small sample of teachers, the fact that we only studied teachers' PCK from observations and interviews, and that we only conducted a content validity in the performance test. However, we believe the findings of the study are crucial in building our understanding of PCK and its influence on student learning. From a methodological point of view, studying PCK and student learning at concept level allowed us to investigate a close relationship between them by exploring how teachers engaged with concepts and how students responded in relation to the concepts in the test.

Word count: 8000

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