Development of Science Teachers' PCK About Waves Through Training in the use of the Ripple Tank Apparatus

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Abstract

This study investigated the effect of in-service training in the use of the ripple tank equipment on science teachers' pedagogical content knowledge (PCK) about the topic of waves. Three Grade 10 Physical Sciences teachers participated in this qualitative case study. The Refined Consensus Model informed the conceptual framework of this study, considering PCK at a topic level within each of the three realms of PCK. The training exposed teachers to the collective realm of PCK with the intention of developing their personal PCK about the topic. Teachers' personal PCK was explored by means of written Content Representations before as well as after the training. After the training, teachers' enacted PCK was observed and video-recorded while teaching the topic of waves to their learners. Pedagogical reasoning was elicited through video stimulated recall interviews. The post-training interviews also provided insight into participants' general views about the in-service training. The results show that the participants' personal PCK improved and that some of the content and skills taught during in-service training were utilized in the enacted PCK of two of the participants, particularly regarding conceptual teaching strategies. Least improvement occurred for the component of teachers' knowledge of learners' understanding. We found evidence that teachers' beliefs influence their pedagogical reasoning, acting as amplifiers and filters to translate newly acquired personal PCK into enacted PCK: teachers who prioritise hands-on experiences and teaching for understanding as opposed to rote learning are more receptive to training in the use of apparatus. The study therefore shows that training in the use of the ripple tank equipment improved in unique ways each of the teachers' PCK about waves.

Keywords: Pedagogical content knowledge, in-service teacher training, waves, ripple tank apparatus

Introduction

Shulman (1986) introduced the construct of pedagogical content knowledge (PCK) to the educational world, claiming that learners require teachers who are not just knowledgeable about the specific subject matter, but who can also transform the content into understandable units for all learners. Thereafter, different PCK models were proposed and several studies were undertaken to characterise PCK and describe its components, leading to a need for agreement on the description of the notion of PCK. Consequently, the consensus model was developed (Gess-Newsome, 2015) at a PCK summit and later followed by the Refined Consensus Model ((RCM); Carlson & Daehler, 2019). Teachers hold their own unique PCK which is gained through practice (Shulman, 1986) and developed and improved through pre-service and in-service education (Barnett & Hodson, 2001), but providing in-service PCK training in all topics within a subject is not practically possible. However, Mavhunga et al. (2016) concluded that teachers can transfer their PCK from one topic to another. It is therefore intrinsically worthwhile to improve a teacher's PCK even if only in one topic.

The topic of waves forms the basis of phenomena experienced in modern communication technology as well as in daily life as sound and light. The topic is included in school curricula worldwide, as well as in South Africa. Within the field of physical sciences education, this topic has been investigated from the perspective of student understanding (e.g. Wittmann, 2002). However, despite its importance in physics, there is a paucity of research on the *teaching* of the topic of waves (Caleon & Subramaniam, 2010), and no studies on PCK in waves were found. The literature also shows that, owing to the theoretical nature of the topic of waves, learners have difficulty understanding the topic (Caleon & Subramaniam, 2010; Sadler & Sonnert, 2016). Van Driel et al. (1998, p. 675) argue that using suitable representations may address learners' challenges:

> The more representations teachers have at their disposal and the better they recognize learning difficulties, the more effectively they can deploy their PCK.

Therefore, learners' difficulties in waves may be addressed if teachers use appropriate equipment to explain the phenomenon of waves and the relationships between the basic physical quantities related to wave motion (Sadler & Sonnert, 2016). In schools, teachers can use slinky springs, tuning forks, oscilloscopes and ripple tanks to illustrate and teach the fundamental concepts of waves. Each of these items of equipment has particular advantages in teaching waves. The main advantage of the ripple tank is that transverse mechanical waves can be physically observed in two dimensions. Furthermore, adjusting the depth of the water and the frequency of the vibrator provides insight into how both the medium and source influence the wavelength, as presented by the wave equation, which applies to all types of waves. The phenomena of superposition and refraction can be observed in two dimensions, thus enhancing understanding of these phenomena also for sound and light. Despite these advantages, the ripple tank apparatus is not available in many South African schools. Lack of apparatus is not the only challenge: teachers are sometimes reluctant to use apparatus in schools where it is available (Hattingh et al., 2007).

We argue that providing ripple tank apparatus and in-service teacher training in schools where needed may enhance teachers' PCK. Improved PCK may lead to better teaching of waves and may improve learner understanding and address learners' misconceptions about waves as argued by Van Driel et al. (1998).

The following research question was formulated: how does in-service training in the use of the ripple tank equipment affect teachers' PCK about the teaching of the topic of waves? Having answered this question and considering the ongoing international focus on PCK

(Carlson & Daehler, 2019; Chan et al., 2018), we believe that this study may prove helpful when making resource decisions about professional learning opportunities for Physical Sciences teachers and in turn, may lead to improved science education.

Literature Review

Understanding the Properties of Waves

Learners find the properties of waves counterintuitive and difficult to comprehend (Caleon & Subramaniam, 2010). These difficulties include the distinction between source and medium, particle motion and wave motion, believing that the speed of a wave in a medium with fixed properties depends on the frequency, and understanding refraction and reflection at the boundary of two media (Caleon & Subramaniam, 2010). Furthermore, Sadler and Sonnert (2016) argue that conceptual and reasoning difficulties arise owing to a lack of understanding of the basic concepts of wave physics, which include wavelength, frequency and propagation speed.

The Nature of PCK

Shulman (1986) proposed that PCK includes two key elements of knowledge, namely, knowledge of the representations of subject matter and the understanding of specific learner difficulties and learner conceptions (Van Driel et al., 1998). Other scholars, e.g. Magnusson et al. (1999) and Rollnick et al. (2008), have expanded the concept of PCK by including other PCK categories of different knowledge bases for teaching. The various conceptualisations of PCK involve differences as well as overlap. Similarities include agreement on the knowledge of representations and strategies, student learning, curriculum and media. Following the PCK summit, Gess-Newsome (2015) explained the consensus model, defining PCK as: (i) a knowledge base that is used in the planning and delivery of topic-specific instruction in a specific classroom context and (ii) as a skill when involved in the act of teaching.

In order to track the development of PCK, it needs to be captured and assessed. Loughran et al. (2004) developed the Content Representation (CoRe) tool to capture PCK on any specific topic. The CoRe tool is a template that can be completed by teachers to present their PCK in an organised way. Firstly, the teacher should divide the topic into a few 'Big Ideas' before responding to prompts about the teaching of each big idea.

Mavhunga and Rollnick (2013) argued that to improve the quality of teaching, the value of PCK lies in its topic-specific nature. Their model of Topic Specific PCK (TSPCK) is described in terms of five components. These are the teachers' knowledge about the *curricular saliency*, *learners' prior knowledge*, *what is difficult and/or easy*, *representations* and *conceptual teaching strategies.* These topic-specific components in the model were explicitly linked to the CoRe prompts.

Recently, the RCM (Carlson & Daehler, 2019) has been proposed. This model identifies three distinct realms of PCK, namely collective PCK (cPCK), personal PCK (pPCK), and enacted PCK (ePCK). It also considers the idea of the role of grain size of PCK, thus PCK at a discipline, topic or concept level. The RCM includes interaction between the three realms of PCK, assuming that cPCK belongs to the profession of teaching and informs the development of teachers' pPCK. In addition, teachers' pPCK informs their ePCK in the classroom environment (Carlson & Daehler, 2019). All three realms of PCK interconnect as teachers apply their PCK during pedagogical reasoning (Chan et al., 2018).

Chan et al. (2018) developed the Grand Rubric (GR), aligned to the RCM. This rubric includes five components: knowledge and skills related to *curricular saliency*, *conceptual teaching strategies (including representations and analogies)*, *student understanding of science*, *integration between pck components* and *pedagogical reasoning.* Teachers' pedagogical reasoning is described as teachers' ability to justify their teaching and decision making by reflecting upon their actions within the context of their classroom.

Conceptual Framework

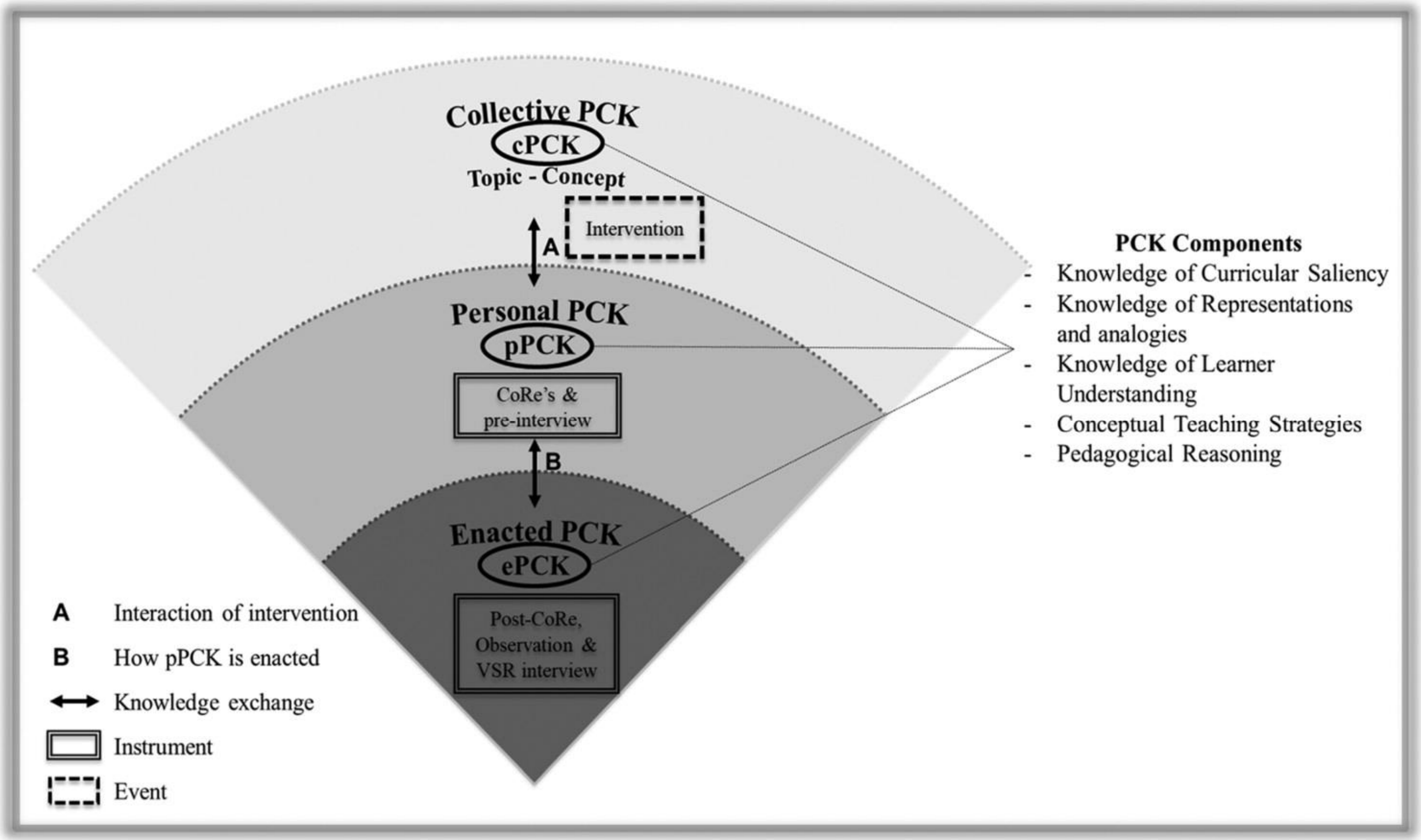
The conceptual framework for this study is based on the RCM, with five PCK components applicable to each of the three realms of PCK, as shown in Figure 1. Our components are based on an amalgamation of the GR and the TSPCK model. Our model includes the component *curricular saliency* as in both models. We combined two components, *learners' prior knowledge* and *what is easy/difficult related to teaching the topic* from the TSPCK model, into one component, *knowledge of learner thinking*, similar to that in the GR. Furthermore, our framework includes *representations and analogies* as a separate component, similar to the TSPCK model, while the GR regards it as part of *conceptual teaching strategies.* We argue that the mere employment of representations and analogies does not constitute a conceptual teaching strategy, although there is overlap. Also, we do not include *integration between PCK components* from the GR because it seems similar to the TSPCK model's description of *conceptual teaching strategies*, which we include. From the GR, we include *Pedagogical reasoning* as we regard it as important to shed light on how in-service training influences the teachers' decision-making and actions within the context of their classrooms (Chan et al., 2018).

Figure 1 shows knowledge exchange (Carlson & Daehler, 2019) as arrows between the PCK realms. Arrow A represents the intervention drawing on the cPCK to develop the pPCK of the participants. Arrow B represents the transfer of pPCK into ePCK. The pre-interviews and pre-CoRes were used to probe the pPCK while the ePCK was explored using the post CoRe and classroom observations, with the video stimulate recall (VSR) interviews probing pedagogical reasoning.

Intervention

The intervention was provided in the form of in-service teacher training. Nivalainen et al. (2010, p. 406) indicate that

courses in practical or laboratory work that target physics teachers should aim at familiarizing the participants with practical work itself, so that they are helped in understanding the purpose of experimental work at school, in learning more of the



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necessary content information, and also so that they are introduced to different instructional approaches.

The training was presented by the third author, who is an experienced physics teacher educator, individually to each teacher, in his/her classroom, in an afternoon session. The intervention was constructed to include knowledge relevant to the Curriculum and Assessment Policy Statement (CAPS) (Department of Basic Education, 2011), centred on the topic of waves. In addition, the plan and structure of the intervention considered the ripple tank teacher guide that accompanied the apparatus. The teacher guide includes notes on the contents of the kit, assembling the ripple tank and use of the stroboscope, generation of planar and circular waves and using the ripple tank to study the property of waves. In addition, it includes four experiments with simple rubrics about reflection, refraction, interference patterns and diffraction of waves in a ripple tank. During the intervention, a schedule was followed to ensure consistency and formality.

The training was introduced by assembling the ripple tank apparatus by both the trainer and teacher. The trainer elaborated on how to further maximize the use of the ripple tank apparatus and on the relevance to the curriculum. The teacher's ideas and normal classroom practice were explored through the pre-interview to determine how they normally teach waves and how teaching waves could be made more effective. The training was interactive, with discussion and hands-on demonstration initiated by the trainer and subsequent hands-on practice and involvement and discussion with the participant. The following wave-concepts were explicitly dealt with in the following order: pulse and wave fronts; wavelength; frequency; period; reflection; refraction; superposition; diffraction; and interference. Pedagogical content knowledge was not discussed explicitly, although the PCK components were implicit in the intervention by logical sequencing of concepts, encouraging the teacher to probe the learners' prior knowledge, while using a specific representation (the ripple tank) and alerting participants to misconceptions that may exist or arise. To address learners' incorrect prior knowledge, the following issues were discussed explicitly as part of the in-service training strategy: bright lines in the projection represent crests, not troughs; the propagation speed remains constant in a given medium when the source frequency is adjusted; and the wavelength changes as described by the wave equation, $v = \lambda \times f$, when only the medium (depth of the water) is changed.

The trainer encouraged the teacher to ask learners to suggest a way to change the speed of the wave, creating an opportunity to mention the misconception that the frequency of the source may influence the speed. As a result, each of the three participants during their respective interventions acknowledged that learners tend to believe that the speed of the wave changes despite the medium (water) remaining unchanged. Furthermore, the apparatus was used to address aspects such as the propagation speed changes while the frequency remains constant and the need not to confuse frequency and speed or frequency and period.

The trainer encouraged teachers to practise using the apparatus to determine the best practical protocol and an effective teaching sequence. In addition, during the intervention, the teachers were reminded to facilitate learner participation, critical reasoning and learners' prior knowledge when teaching waves using the ripple tank apparatus.

Research Methodology

Design

This study followed a multimethod qualitative design. The case study approach allowed multiple sources and techniques (Baskarada, 2014). The intervention drew on the cPCK belonging to the profession of science education to develop the pPCK of the participants (Carlson & Daehler, 2019). The participants' pPCK was captured using the CoRe tool, prior to and after the intervention, to assess the improvement, if any, of the teachers' pPCK. Pre-interviews were used to support the pre-CoRe. The teachers' ePCK after the intervention was accessed through lesson observations and video-recordings of the lessons, while pedagogical reasoning was drawn from VSR interviews. The trustworthiness is supported by the use of multiple data sources and expert validation of instruments and data interpretation. Ethical clearance was granted by the institution that undertook the study and the participants provided informed consent to participate.

Sample

Three participants were selected purposefully and conveniently. The participants did not have prior access to a functional ripple tank and had no previous formal in-service teacher training on using the ripple tank apparatus. In addition, the participants had to be qualified to teach Physical Sciences, proficient in English, willing to participate and employed at city schools within convenient reach of the researchers. The selected participants and their relevant schools were provided with the ripple tank apparatus and in-service teacher training at no cost. The participants included one female and two male Grade 10 Physical Sciences teachers from three schools, using the pseudonyms Jessica, Tshuma and Craig, respectively, to protect their identities.

Data Analysis

The relevant content for the study is based on the fundamental concepts of wavelength, frequency and superposition as presented in the national curriculum of South Africa, available in the CAPS Document for Grade 10 learners (Department of Basic Education, 2011). These concepts were pre-selected by the researchers to be used in the CoRe template as 'Big Ideas' (Loughran et al., 2004), which narrowed down the scope of the study.

For the purpose of scoring the CoRes, a rubric from Coetzee (2018) was adapted to the topic of waves and to the GR (Carlson & Daehler, 2019). *Pedagogical reasoning* was excluded from the CoRes as this component can only be assessed fairly from classroom observations and VSR interviews. The rubric used the three-point scale of Limited, Adequate and Rich pertaining to the topic of waves. To assist in scoring, an expert CoRe was developed to provide an indication of the PCK expected from teachers, based on the expectations of the CAPS document. Both the expert CoRe and the scoring rubric were developed by the first

Table 1. Section from the rubric for pedagogical content knowledge (PCK), showing scoring criteria for the components *representations*, *conceptual teaching strategies* and *pedagogical reasoning*.

	Limited	**Adequate**	**Rich**
Representations	The use of representations is restricted to drawings also available in textbooks. Does not make an effort to incorporate representations to support conceptual understanding.	Use of representations restricted to one type. Uses objects as illustrations or artefacts. Uses a representation with no apparent conceptual development in learners.	Makes extensive use of representations in combination with the ripple tank. Uses representations to support understanding of concepts. Uses representations effectively to stimulate conceptual reasoning. Uses a variety of representations with logical sequencing in combination with appropriate questions.
Conceptual teaching strategies	Relies mostly on explaining and telling. Portrays a teaching style aimed towards—*lecturer*. Questions elicit chorus or yes/no responses. Answers own questions before learners make an attempt. Ignores learners' answers when not in line with the expected answer. Does not show awareness when learners reveal the existence of misconceptions.	Portrays a teaching style aimed towards—*demonstrator or hybrid*. Questions asked mostly require rote learning. Answers own questions after only one or two attempts by learners—does not rephrase questions. Addresses misconceptions through procedural teaching. Uses representations in combination with direct instruction—telling learners what they are supposed to see or as confirmation of theory only.	Portrays a teaching style aimed towards—*facilitator or delegator*. Shows an attempt to work towards problem solving and inquiry. Asks questions to elicit learner thinking and that require conceptual reasoning. Shows effective integration of pre-concepts. Shows awareness of typical learner errors and misconceptions and works towards conceptual change. Waits for responses and does not answer own questions; rephrases questions.
Pedagogical reasoning (determined during VSR interview)	Pays no attention to the decisions and actions chosen. Actions chosen are not relevant to the classroom context. No correlation between the personal PCK and the enacted PCK	Able to identify their actions and decisions but fails to explain or provide a rationale for the decisions made and actions taken.	Explains in full and with depth the rationale, decisions and actions chosen. The strategy is fully accounted for. Actions chosen are relevant to the classroom context and why the actions were chosen are explained. Knowledge and reasoning (personal PCK) correlated to the implementation knowledge/skills and reasoning (enacted PCK). Sensitivity and responsiveness seen towards the context.

author, and validated by the second and third authors of this study. An illustrative section of this rubric is shown in Table 1.

To assess enacted PCK, lessons were observed and video-recorded. The videos were divided into numbered sections, and a narrative account was written for each section. The sections were coded to identify evidence of enacted PCK that related to the wave concepts discussed during the intervention.

Results

The participants' pre- and post-CoRe responses were compared to explore how the intervention contributed to the development of their pPCK. It was not possible to directly observe changes in their ePCK, as the teaching of the topic was observed only after the intervention and it is known that the teachers had not used the ripple tank before. We therefore report on remarks and events during the lessons that illustrated similarities to events from the intervention which were regarded as evidence of the influence of the intervention.

Table 2 summarizes the participants' scores across the components of the pPCK and ePCK for the three big ideas. It was evident that there was some improvement in the participants' pPCK after the intervention. The discussion of results below is presented per case to give a holistic picture of the personal and enacted PCK. The discussion is limited to improvements in the pPCK and any significant findings for each participant's ePCK. In addition, Table 3 summarises the instances where misconceptions and difficulties were addressed by the participants in the CoRe and during lesson observations.

Case Study 1—Jessica

Jessica was teaching at a school that has a physics laboratory with some apparatus and equipment. However, she taught in a conventional classroom. Jessica's normal classroom practice, before the intervention, included practical time and group work when she deemed it appropriate.

pPCK Based on the Pre- and Post-CoRe

Jessica's scores in the pre-and post-CoRe improved in three of the five PCK components as displayed in Table 2. For the component *curriculum saliency,* she improved her scores for the big ideas of *frequency* as well as for *superposition*, by adding aspects discussed during the intervention. In her post-CoRe, she added the concept of interference, revealing her knowledge of why learners should understand superposition, which can be linked to the intervention. Jessica's knowledge of *learners' understanding*, which was rich in two of the big ideas, remained unchanged. Her score in the component *representations* improved for the big idea of *wavelength*, where she added how she would use the ripple tank to illustrate wave fronts and the effect of changing the source's oscillation frequency. This improvement can be directly linked to the intervention.

Table 2. Summary of participants' personal PCK (pPCK) and enacted PCK (ePCK) across the five PCK components for the three big ideas.

		Curriculum saliency			*Learners' understanding*			*Representations*			*Conceptual teaching strategies*			*Pedagogical reasoning*
Participant	**Big idea**	**Pre**	**Post**	**Enacted**	**Pre**	**Post**	**Enacted**	**Pre**	**Post**	**Enacted**	**Pre**	**Post**	**Enacted**	**Post**
Jessica	Wavelength	R	R	R	R	R	A	L	**A**	A	L/A	**A/R**	R	*L*
	Frequency	A	**A/R**	R	A	A	A	A	**R**	A	A	**A/R**	A/R	*L*
	Superposition	A	**A/R**	R	R	R	R	A	A	R	A	**A/R**	R	*R*
Tshuma	Wavelength	A	A	R	A	A	R	L	**A**	L	L	**A**	A	*L*
	Frequency	A	**R**	R	A	A	R	L	L	L	L	**A/R**	A	*L*
	Superposition	L/A	**A**	—	L	**A/R**	—	A	A	—	L	**A/R**	—	-
Craig	Wavelength	L	**L/A**	L	A	A	A	L	L	R	A	A	L/A	*R*
	Frequency	L	L	A	A	A	A	L	L	R	L/A	L/A	L/A	*R*
	Superposition	L/A	L/A	A	A	A	A	L	L	R	A	A	A	*R*

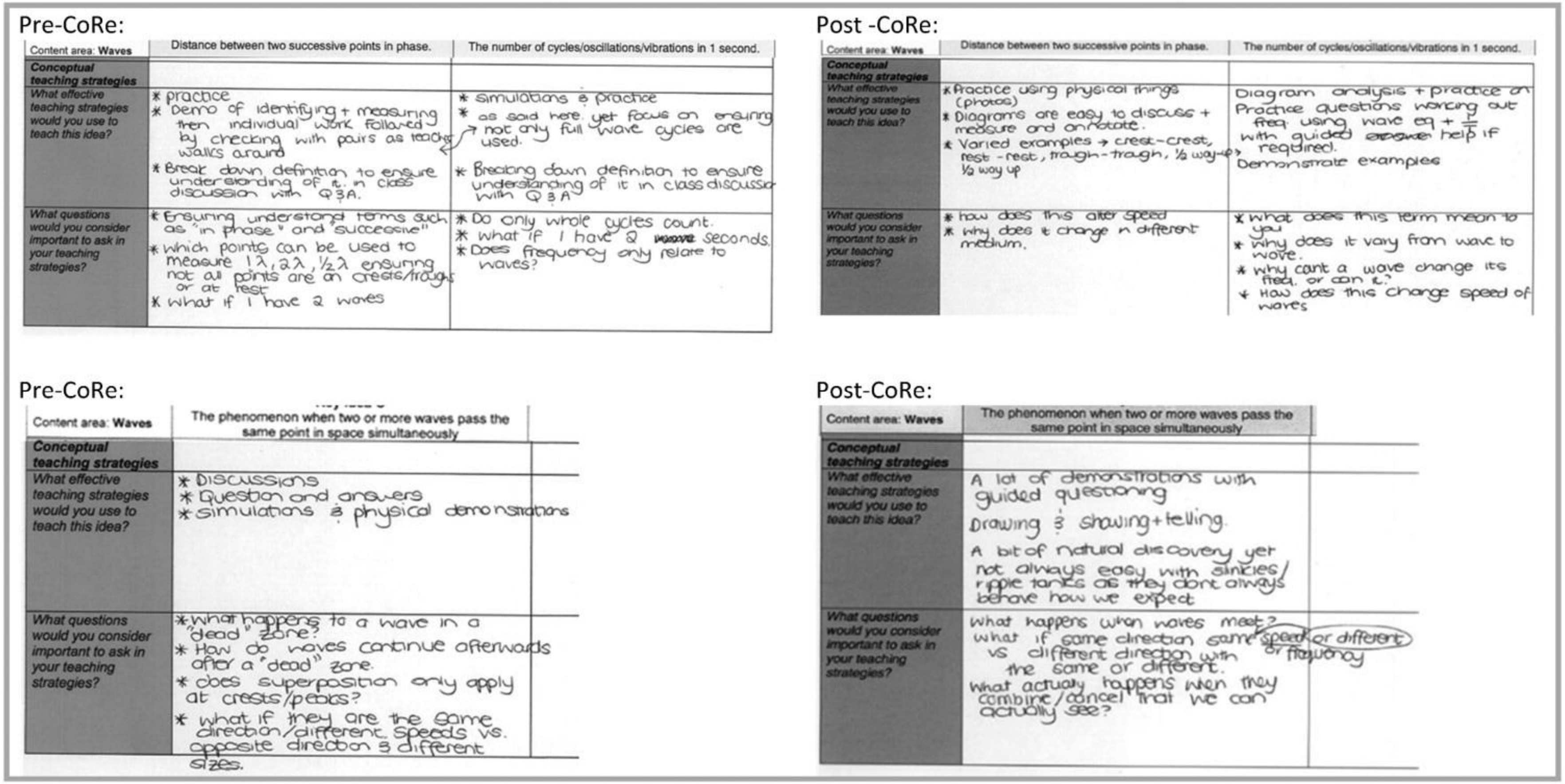
L, Limited; A, adequate; R, rich; —, not observed.

Bold indicates improved scores.

Table 3. The participants' pPCK and ePCK for the difficulties and misconceptions as captured in the different data sources.

Participant	**Jessica**				**Tshuma**				**Craig**			
	pPCK			**ePCK**	**pPCK**			**ePCK**	**pPCK**			**ePCK**
Ideas that learner finds difficult and misconceptions	**Interview**	**Pre-CoRe**	**Post-CoRe**	**Observation**	**Interview**	**Pre-CoRe**	**Post-CoRe**	**Observation**	**Interview**	**Pre-CoRe**	**Post-CoRe**	**Observation**
Light and dark lines seen in the ripple tank projection	×	×	×	✓	×	×	✓	×	×	×	✓	✓
Relationship between f and λ in $v = f \times \lambda$	×	×	×	×	×	✓	✓	×	×	×	✓	✓
Confusion between speed of a wave and frequency	×	×	✓	✓	×	×	✓	×	×	✓	×	✓
Confusion between frequency and period	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×

✔, Mentioned; ✖, not mentioned. Shaded, post-intervention; not shaded, pre-intervention.



Pre-CoRe:

Content area: Waves	Distance between two successive points in phase.	The number of cycles/oscillations/vibrations in 1 second.
Conceptual teaching strategies		
What effective teaching strategies would you use to teach this idea?	* practice * Demo of identifying + measuring then individual work followed by checking with pairs as teacher walks around * Break down definition to ensure understanding of it in class discussion with Q3A.	* simulations & practice * as said here yet focus on ensuring not only full wave cycles are used. * Breaking down definition to ensure understanding of it in class discussion with Q3A
What questions would you consider important to ask in your teaching strategies?	* Ensuring understand terms such as "in phase" and "successive" * Which points can be used to measure 1λ, 2λ, ½λ ensuring not all points are on crests/troughs or at rest * What if I have 2 waves	* Do only whole cycles count. * What if I have 2 seconds. * Does frequency only relate to waves?

Post -CoRe:

Content area: Waves	Distance between two successive points in phase.	The number of cycles/oscillations/vibrations in 1 second.
Conceptual teaching strategies		
What effective teaching strategies would you use to teach this idea?	* Practice using physical things (photos) * Diagrams are easy to discuss + measure and annotate. * Varied examples → crest-crest, rest-rest, trough-trough, ½ way-up → ½ way up	Diagram analysis + practice on Practice questions working out freq. using wave eq + 1/p with guided help if required. Demonstrate examples
What questions would you consider important to ask in your teaching strategies?	* how does this alter speed * why does it change in different medium.	* what does this term mean to you * Why does it vary from wave to wave. * why cant a wave change its freq. or can it.? * How does this change speed of waves

Pre-CoRe:

Content area: Waves	The phenomenon when two or more waves pass the same point in space simultaneously
Conceptual teaching strategies	
What effective teaching strategies would you use to teach this idea?	* Discussions * Question and answers * simulations & physical demonstrations
What questions would you consider important to ask in your teaching strategies?	* What happens to a wave in a "dead" zone? * How do waves continue afterwards after a "dead" zone. * does superposition only apply at crests/peaks? * what if they are the same direction/different speeds vs. opposite direction & different sizes.

Post-CoRe:

Content area: Waves	The phenomenon when two or more waves pass the same point in space simultaneously
Conceptual teaching strategies	
What effective teaching strategies would you use to teach this idea?	A lot of demonstrations with guided questioning Drawing & showing + telling. A bit of natural discovery yet not always easy with slinkies/ripple tanks as they dont always behave how we expect
What questions would you consider important to ask in your teaching strategies?	What happens when waves meet? What if same direction same speed or different or frequency vs different direction with the same or different. What actually happens when they combine/cancel that we can actually see?

Figure 2. Pre- and post-Content Representation (CoRe) for Jessica pertaining to knowledge and skills related to *conceptual teaching strategies*.

For the *conceptual teaching strategies* (Figure 2), Jessica had improved scores for all three big ideas by displaying a better understanding of the use of appropriate questions and representations to address common learner misconceptions, thereby supporting the learners' conceptual understanding. As such, she integrated PCK components well, resulting in rich *conceptual teaching strategies*.

ePCK Through Classroom Observations and the VSR Interview

In terms of knowledge of *learners' understanding*, Jessica addressed three of the four difficulties and misconceptions which were discussed during the intervention (see Table 3). Three of the difficulties were not recorded in her pre-interview or pre-CoRe, suggesting an improvement in her pPCK and ePCK that can be attributed to the intervention. Specifically, during Jessica's lessons, she discussed the concepts of superposition and interference using the ripple tank, emphasising the light and dark lines seen in the projection. In addition, she explained in her post-CoRe and lessons that learners often refer to a 'fast wave' to describe a high frequency, while it actually refers to a high speed of propagation. Jessica did not mention either of these difficulties before the intervention, suggesting that she learnt about them in the intervention. It seems that she prioritised conceptual understanding and that her pre-existing insight into learners' understanding made her receptive to the training.

Regarding *representations*, Jessica employed the ripple tank to demonstrate the concepts of reflection, refraction, diffraction and superposition as taught in the intervention. However, she did not demonstrate how increasing the frequency shortens the wavelength or use the apparatus to distinguish between speed and frequency, missing the opportunity to utilise the equipment to show a practical application of the wave equation. She explained her decision during the VSR interview:

> I didn't think they would be able to really see that clearly. I could supposedly have changed the frequency, and I think I did try [not observed], but I was also scared that they wouldn't see the effects.

Her explanation suggested that she lacked confidence despite the training. Consequently, her *pedagogical reasoning* was rated as *limited* for both of these concepts. It seems that she did not practise the manipulation of depth and frequency after the training. Nevertheless, Jessica's pPCK scores as reported in her post-CoRe were similar to her ePCK scores (Table 2), supporting the notion that Jessica was able to transfer most of her improved pPCK into ePCK.

Case Study 2—Tshuma

Tshuma did not have access to a school laboratory and used a conventional classroom to teach the Physical Sciences lessons. Tshuma's school was poorly resourced with a dysfunctional ripple tank. Before the intervention, practical work was minimal; instead he relied on YouTube videos and past examination papers for teaching. This is despite his claim that he believed in a 'hands-on' approach.

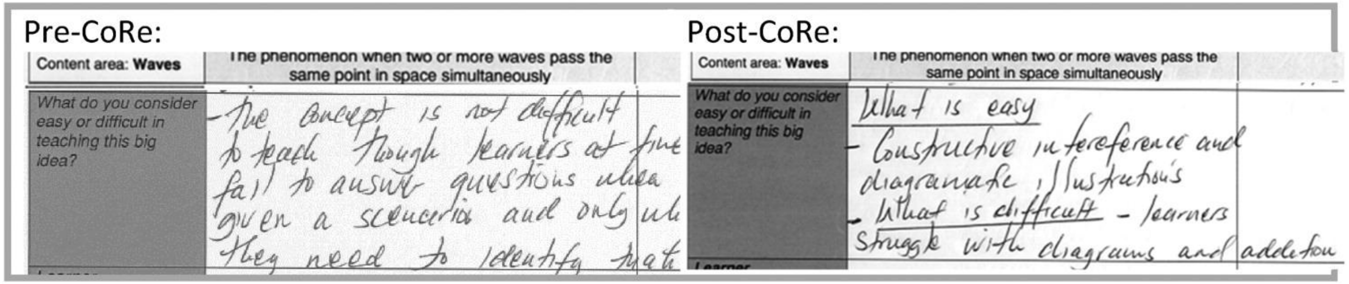


Figure 3. Sections from the pre- and post-CoRe for Tshuma pertaining to knowledge and skills related to *learner understanding*.

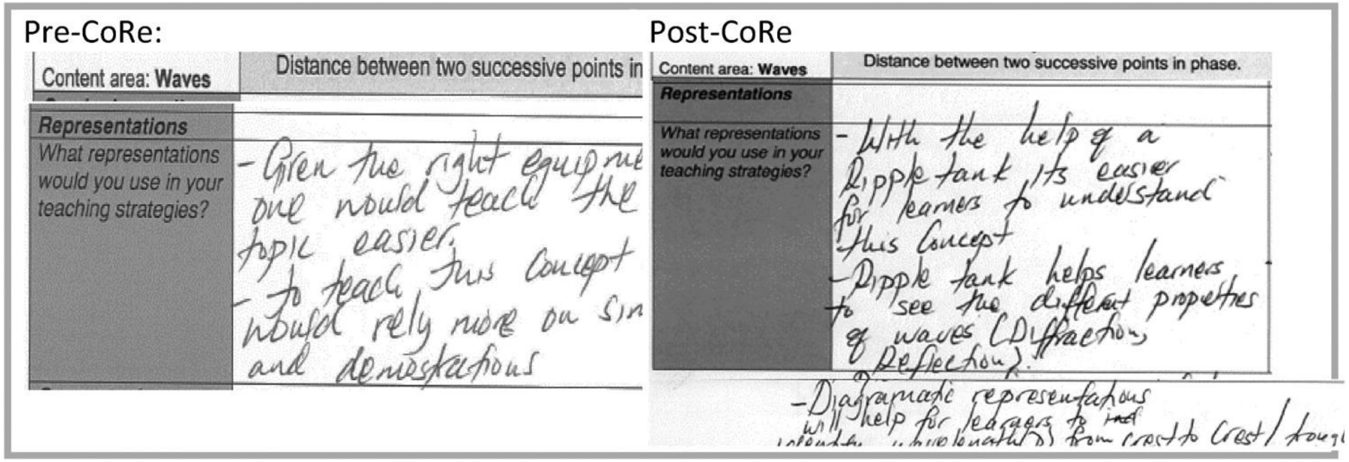


Figure 4. Sections from the pre- and post-CoRe for Tshuma pertaining to knowledge and skills related to *representations*.

pPCK Using the Pre-and Post-CoRe

Tshuma's scores (Table 2) improved for *curriculum saliency* for the big ideas of *frequency* and *superposition*. In his post-CoRe, for *frequency*, Tshuma included its unit and symbol and for *superposition* he displayed additional knowledge by referring to a concept required for Grade 11, which is the diffraction pattern of light seen through a single slit. After the intervention, he was the only participant who had an improved score for the component of *learners' understanding* (Figure 3). For *superposition*, his post-CoRe response mentioned the use of diagrams to explain constructive interference. This can be linked to the intervention, where a diagram of superposition was discussed and drawn on the board. Tshuma had an improved score for *representations* for the big idea of *wavelength* (Figure 4), where he indicated how diagrammatic representations enhance learner understanding.

Tshuma also displayed improved levels for all three big ideas for the component of *conceptual teaching strategies* by suggesting the use of appropriate questions and representations to address common learner misconceptions, displaying evidence of integration of PCK components.

ePCK Through Classroom Observations and the VSR Interview

During his lessons, Tshuma discussed only one of the difficulties and misconceptions indicated in Table 3, despite mentioning all of these difficulties in his post-CoRe. Two new ideas mentioned in his post-CoRe about the light and dark lines seen in the ripple tank projection and the confusion between the speed of a wave and frequency were not mentioned in class. Furthermore, he mentioned the relationship involving frequency and wavelength in both CoRes but not during the observed lessons. The only learner difficulty discussed in class was about frequency and period, although he had this knowledge before the intervention as it was included in his pre-CoRe.

Unexpectedly, Tshuma chose not to use the ripple tank during his lessons, in line with his belief that there is no time for practical work:

> I would have loved to because with my learners, the way they are so keen to learn, it was going to help them a lot. So, the only key factor there was time.

This is despite his enthusiasm about the training and the fact that in his pre-CoRe he wrote: 'given the right equipment one would teach the topic easier' (Figure 4). Consequently, Tshuma's *pedagogical reasoning* was scored *limited*. It seems that the influence of the training was filtered by his beliefs and habits of teaching to the test and providing visual experiences. Instead of using the ripple tank, Tshuma used the lesson time to focus on questions from past examination papers. Despite the improvement in his pPCK as revealed in his CoRe scores (see Table 2), he did not translate his pPCK into ePCK.

Case Study 3—Craig

Craig taught Physical Sciences in a conventional classroom and did not have a Physical Sciences laboratory. Like Tshuma, he had very little access to equipment and no ripple tank apparatus. Instead, Craig made use of simulations, stating that learners better understand and remember a concept if exposed to visualizations.

pPCK Using the Pre-and Post-CoRe

According to Table 2, Craig showed an improvement for the big idea of *wavelength* for the component of *curriculum saliency.* In the post-CoRe Craig explained how the light lines observed in the projection of the ripple tank represent the crests while the darker lines are the troughs. This improvement in knowledge can be ascribed to the intervention as it was not mentioned in any of his pre-intervention responses. There was no improvement in his pPCK for any of the other components.

ePCK Through Classroom Observations and the VSR Interview

During Craig's lessons, in terms of *representations*, his ePCK was scored *rich*, showing an improvement compared with the pPCK he reported. It is not possible to conclusively attribute the improvement to the intervention, as his post-CoRes were similar to the pre-CoRes. For *learners' understanding*, he discussed three of the difficulties and misconceptions as shown in Table 3. Two of these were not indicated in his pre-interview and pre-CoRe, suggesting, although not conclusively, that his pPCK improved and was translated into ePCK in this respect. Craig clearly demonstrated most of the wave concepts using the apparatus. However, the confusion between frequency and period was not covered in the lessons although it was indicated in his pre-interview, pre-CoRe and post-CoRe. Compared with the other teachers, Table 2 shows that Craig generally had the least improved scores in reported pPCK, but the highest scores in ePCK for *representations* and *pedagogical reasoning*.

When Craig was asked upon reflection if he would make any changes to his lessons that were observed, he answered:

> [I would] introduce the wave on its own. Showing the crest and the trough and the rest position before doing demonstration … on the ripple tank. I think that way they will understand even more when you are doing the demonstrations.

Craig gave a full account about the rationale behind the decisions and actions that he undertook. He proposed how he would adjust his teaching strategy to benefit learner understanding and included concrete examples, i.e. showing the crest. He showed sensitivity and responsiveness towards the context by indicating where he could improve his actions when reflecting on the actions taken. For this reason, we considered his *pedagogical reasoning rich*.

Discussion

Collectively, the participants' pPCK showed most improvement for *conceptual teaching strategies* across the three big ideas. A similar finding was observed by Pitjeng-Mosabala and Rollnick (2018), who explored the development of novice unqualified graduate teachers' TSPCK in teaching the particulate nature of matter in South African classrooms.

According to Mavhunga and Rollnick (2016), rich conceptual teaching strategies require the integration and effective interaction of the other components. As such, we propose that the improvements for *conceptual teaching strategies* can be attributed to the integration of improvements in the other components. This claim supports Carlson and Daehler's (2019) suggestion that, to make concepts understandable to learners, teachers must also have an understanding of the other PCK components.

Second best for improved pPCK was the component *curricular saliency.* Jessica and Tshuma improved in *representations* while Tshuma was the only participant to show an improvement in the component *learners' understanding.* Our results therefore support those of Coetzee et al. (2020) and Mavhunga et al. (2016), who found little improvement in teachers' knowledge of *learners' understanding*.

Regarding ePCK, the knowledge taught during the in-service training was visible in the lessons of all of the participants, although in unique ways for each participant. Jessica had improved pPCK which was transferred into ePCK. Differently, Tshuma showed improved pPCK, although it was not utilised in ePCK. Craig's improvement in pPCK was modest but was transferred adequately into ePCK for most components. However, for *representations*, his ePCK was rich, which was better than what he reported, suggesting a practical orientation and positive attitude to practical learning experiences.

The RCM as well as the earlier Consensus Model suggest that teachers' beliefs about teaching act as amplifiers or filters (Carlson & Daehler, 2019) of what teachers retain from an experience such as this intervention. In Jessica's case the positive effect of the intervention on her ePCK was possibly amplified by the fact that she prioritises teaching for understanding and learning through experimental inquiry, as seen in her CoRes. Even though Tshuma's pPCK improved after the intervention, the effect on his ePCK was filtered by his belief in exam preparation and the low priority he gave to hands-on experiences. For Craig, the effect of the intervention was mostly visible in his enactment of *representations*, in line with his belief in the value of practical experiences.

Time constraints were identified as a challenge by both Tshuma and Craig, which may result in avoiding equipment use, as reported by others (Hattingh et al., 2007; Ramatlapana & Makonye, 2012). Avoiding the use of equipment suggests poor decision-making and inadequate *pedagogical reasoning*.

Limitations to this study must be acknowledged. As for all case studies, results should not be generalised. Furthermore, it is possible that the teachers would not report their entire pPCK when completing the CoRes, neither would they enact their entire pPCK. Consequently, this may indicate that the one manifestation of PCK would not necessarily be a true reflection of the other, supporting the results of Mazibe et al. (2020). This may explain the discrepancies between pPCK and ePCK in some of the components as found for both Tshuma and Craig, showing the importance of observing a teacher's ePCK in the actual classroom over and above assessing their pPCK.

Although this study was conducted for the ripple tank apparatus only, we recommend that training in the use of apparatus be included in professional learning opportunities for teachers, and that more research be conducted on the effects of such interventions on PCK, teaching and learning.

Concluding Remarks

In conclusion, the findings of this study indicate that supplying the ripple tank apparatus and providing in-service training had a positive influence on the teachers' PCK, although in unique ways for each teacher. The findings further suggest that a teacher who prioritizes hands-on experiences and teaching for understanding as opposed to rote learning is more receptive to the cPCK that was imparted during the intervention.

The findings further contribute to the idea that teacher training should be considered with the supply of Physical Sciences equipment, despite the concern over its monetary implications and time constraints. As a result, we envisage that this study will guide school administrators, teachers, the education department and the private sector when they make decisions about resources in professional learning opportunities for Physical Sciences teachers.

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References

Barnett, J., & Hodson, D. (2001). Pedagogical context knowledge: Toward a fuller understanding of what good science teachers know. *Science Education*, *85*(4), 426–453. https://doi.org/10.1002/sce.1017

Baskarada, S. (2014). Qualitative case study guidelines. *The Qualitative Report*, *19*(40), 1–25. Retrieved from https://nsuworks.nova.edu/tqr/vol19/iss40/3

Caleon, I., & Subramaniam, R. (2010). Development and application of a three-tier diagnostic test to assess secondary students' understanding of waves. *International Journal of Science Education*, *32*(7), 939–961. https://doi.org/10.1080/09500690902890130

Carlson, J., & Daehler, K. R. (2019). The refined consensus model of pedagogical content knowledge in science education. In A. Hume, R. Cooper, & A. Borowski (Eds.), *Repositioning pedagogical content knowledge in teachers' knowledge for teaching science* (pp. 77–92). Springer Nature.

Chan, K. K. H., Rollnick, M., & Gess-Newsome, J. (2018). A grand rubric for measuring science teachers' pedagogical content knowledge. In A. Hume, R. Cooper, & A. Borowski (Eds.), *Repositioning pedagogical content knowledge in teachers' knowledge for teaching science* (pp. 251–269). Springer Nature.

Coetzee, C. (2018). *The development of pre-service teachers' pedagogical content knowledge in electromagnetism* [Unpublished doctoral dissertation]. University of Pretoria.

Coetzee, C., Rollnick, M., & Gaigher, E. (2020). Teaching electromagnetism for the first time: A case study of pre-service science teachers' enacted pedagogical content knowledge. *Research in Science Education*, 1–22. https://doi.org/10.1007/s11165-020-09948-4

Department of Basic Education. (2011). *Curriculum and assessment policy statement. Grades 10–12 Physical sciences*. Government Printer.

Gess-Newsome, J. (2015). A model of teacher professional knowledge and skill including PCK. In A. Berry, P. Friedrichsen, & J. Loughran (Eds.), *Re-examining pedagogical content knowledge in science education* (pp. 28–42).

Hattingh, A., Aldous, C., & Rogan, J. (2007). Some factors influencing the quality of practical work in science classrooms. *African Journal of Research in Mathematics, Science and Technology Education*, *11*(1), 75–90. https://doi.org/10.1080/10288457.2007.10740613

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

Magnusson, S., Krajcik, J., & Borko, H. (1999). Nature, sources, and development of pedagogical content knowledge for science teaching. In J. Gess-Newsome & N. G. Ledermann (Eds.), *Examining pedagogical content knowledge* (pp. 95–132). Kluwer Academic.

Mavhunga, E., Ibrahim, B., Qhobela, M., & Rollnick, M. (2016). Student teachers' competence to transfer strategies for developing PCK for electric circuits to another physical sciences topic. *African Journal of Research in Mathematics, Science and Technology Education*, *20*(3), 299–313. https://doi.org/10.1080/18117295.2016.1237000

Mavhunga, E., & Rollnick, M. (2013). Improving PCK of chemical equilibrium in pre-service teachers. *African Journal of Research in Mathematics, Science and Technology Education*, *17*(1–2), 113–125. https://doi.org/10.1080/10288457.2013.828406

Mavhunga, E., & Rollnick, M. (2016). Teacher-or learner-centred? Science teacher beliefs related to topic specific pedagogical content knowledge: A South African case study. *Research in Science Education*, *46*(6), 831–855. https://doi.org/10.1007/s11165-015-9483-9

Mazibe, E. N., Coetzee, C., & Gaigher, E. (2020). A comparison between reported and enacted pedagogical content knowledge (PCK) about graphs of motion. *Research in Science Education*, *50*(3), 941–964. https://doi.org/10.1007/s11165-018-9718-7

Nivalainen, V., Asikainen, M. A., Sormunen, K., & Hirvonen, P. E. (2010). Preservice and inservice teachers' challenges in the planning of practical work in physics. *Journal of Science Teacher Education*, *21*(4), 393–409. https://doi.org/10.1007/s10972-010-9186-z

Pitjeng-Mosabala, P., & Rollnick, M. (2018). Exploring the development of novice unqualified graduate teachers' topic-specific PCK in teaching the particulate nature of matter in South Africa's classrooms. *International Journal of Science Education*, *40*(7), 742–770. https://doi.org/10.1080/09500693.2018.1446569

Ramatlapana, K., & Makonye, J. P. (2012). From too much freedom to too much restriction: The case of teacher autonomy from national Curriculum Statement (NCS) to Curriculum and Assessment Statement (CAPS). *Africa Education Review*, *9*(SUPP/1), S7–S25. https://doi.org/10.1080/18146627.2012.753185

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

Sadler, P. M., & Sonnert, G. (2016). Understanding misconceptions: Teaching and learning in middle school physical science. *American Educator*, *40*(1), 26–32.

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

Van Driel, J. H., Verloop, N., & de Vos, W. (1998). Developing science teachers' pedagogical content knowledge. *Journal of Research in Science Teaching*, *35*(6), 673–695. https://doi.org/10.1002/(SICI)1098-2736(199808)35:6<673::AID-TEA5>3.0.CO;2-J

Wittmann, M. (2002). The object coordination class applied to wave pulses: Analysing student reasoning in wave physics. *International Journal of Science Education*, *24*(1), 97–118. https://doi.org/10.1080/09500690110066944