Gaps in teacher competencies linked to inquiry-based practical work in certain resource-constrained South African physical sciences classrooms

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Abstract. Dwindling learner interest in science is a threat to economic development and scientific research. While the inquiry-based teaching and learning strategy in science education can contribute in countering this threat, the required teacher professional development efforts are not always linked to the actual pedagogical experiences and needs of participants. With this in mind, we focussed on the case of two resource-constrained South African schools. The purpose was to identify gaps in teacher competencies linked to the routine implementation of Inquiry-Based Practical Work in physical sciences classrooms. In this regard, we used a conceptual framework incorporating the Technological, Pedagogical, and Content Knowledge (TPACK) framework. This was coupled with a multi-method data collection technique and the inductive technique in thematic analysis. The results consist of gaps in Content Knowledge, Pedagogical Knowledge, Technological Knowledge, Technological Pedagogical Knowledge, and certain professional values. These results have significant implications in relation to evidence-based teacher professional development practice and research in the study context and possibly beyond.

1. Introduction

1.1. Theoretical background

Internationally, learner attitude towards science is becoming less positive during the school years [1]. At the secondary school level, there is a decline in learner interest in physics, chemistry, and other science disciplines [see e.g., 2]. These trends are likely to adversely affect scientific research and economic development, given that science is an important factor in socio-economic progress [see e.g., 3]. In fact, science literacy is increasingly being linked to economic growth, in addition to being necessary when finding solutions to complex environmental and social problems [4].

Possible perspectives for tackling the problem of the link between learners and science include the developmental, identity-based, and instructional type and quality [5]. This study falls under the last perspective. The high theoretical content of such sciences as physics and chemistry makes them less interesting [6]. Actually, motivating learners and sustaining their interest is one of the biggest challenges in chemistry teaching [7]. In this regard, strategies such as problem- and inquiry-based teaching and learning are needed. Thus, the All European Academies Working Group [8], for example, noted the role of Inquiry-Based Science Education (IBSE) in maintaining the passion for science among the young and in preparing a scientific and technical workforce adequate in today‟s knowledge-based societies.

IBSE engages learners in such authentic scientific practices as asking questions about the physical world, investigating these questions, and formulating explanations [9, 10]. This strategy yields affective and cognitive learner benefits. For example, IBSE enables learners to better understand scientific procedures and concepts than through rote learning [11]. This is while enhancing learner engagement, interest, and motivation [see e.g., 12].

1.2. Research focus: Problem and purpose

Despite being receptive to Inquiry-Based Science Education (IBSE), many teachers around the world experience implementation constraints [e.g., 13, 14]. The constraints include concerns linked to the grading of learners, safety, and the availability of time [e.g., 15]. Also, some teachers have inadequacies in such competencies as skills and knowledge linked to the implementation inquiry-based science lessons [16]. Thus, the need for the enhancement of such teacher competencies has been noted by researchers [e.g., 17] and science teachers themselves [18].

The presented study focussed on IBSE in the context of practical work in certain resource-constrained South African physical sciences classrooms. The curriculum for these classrooms requires the engagement of learners in practical work involving inquiry [19]. In the presented research, we refer to such practical work as Inquiry-Based Practical Work (IBPW). IBPW consists of experiences in which learners collaboratively manipulate hands-on science education equipment and materials (SEEMs); possibly computer-based SEEMs; coupled with existing data sets [20]. This is in order to gain an understanding of the natural world as they engage in scientific practices through structured, directed, or open inquiry. This type of practical work is useful in promoting greater interest in science among learners [21]. However, it is rather confirmatory practical work that is prevalent in physical sciences classrooms in resource-constrained South African schools [e.g., 22, 23].

The competencies of teachers in relation to knowledge and beliefs regarding learning, teaching, and content are critical factors regarding how they teach [24]. That being said, the likelihood of an increase in teacher competencies, coupled with an enhancement in their classroom practices, is more when Professional Development (PD) is directly linked to routine pedagogical experiences [25]. However, in South Africa, teacher PD efforts do not always incorporate the actual needs of the participants [26]. Thus, in order to inform evidence-based PD in the implementation of IBPW, the purpose of the presented research was to identify gaps in the competencies (such the skills and knowledge) of physical sciences teachers in participating resource-constrained South African schools.

2. Conceptual Framework

2.1. Overarching theoretical basis

The Interconnected Model of Teachers' Professional Growth discussed in Clarke and Hollingsworth [27], is the overarching theoretical basis in this study. The model is shown in figure 1. Based on this model, effective teacher professional development occurs through reflection and enactment in four domains. The domains consist of the external domain involving external sources of information, stimulus, and support; the domain of practice which includes experimentation in the classroom; the domain of consequence containing salient learning outcomes; and the personal domain which encompasses teacher competencies consisting of knowledge, attitudes, and beliefs.

Through experimentation with a new strategy, a change in the domain of practice, the teacher could develop new knowledge or a belief, which is a change in the personal domain [27]. In the domain of consequence, this can yield a change in the teacher's perception of salient outcomes linked to classroom practice. The change occurs within the constraints and affordances of the professional environment [29].

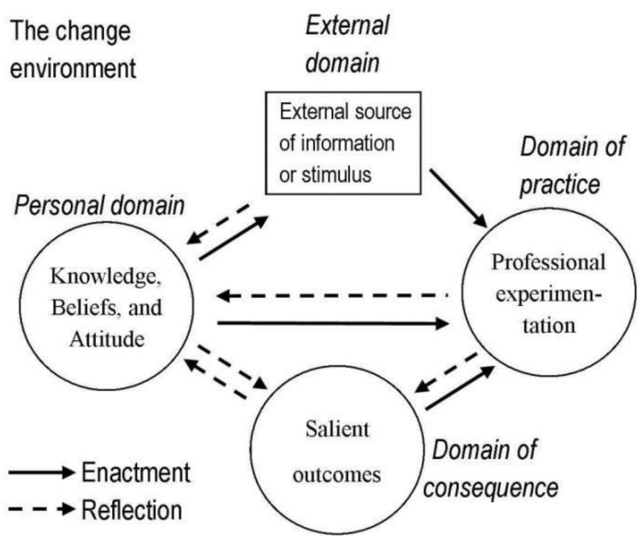

Figure 1. Interconnected Model of Teacher's Professional Growth [28].

2.2. Domain of practice: Inquiry-Based Practical Work (IBPW)
In the domain of practice of the Interconnected Model of Teachers' Professional Growth (figure 1), IBPW is the new strategy that science teachers would have been experimenting. Based on the strategy, the teacher engages learners in such scientific practices as asking questions, developing and applying models; designing and conducting investigations; data analysis and interpretation; using computational and mathematical thinking; participation in evidence-based arguments; in addition to the evaluation and communication of information [30]. However, in relation to the incorporation of these practices in the classroom, different strategies in practical work do not have the same capability. The strategies range from a teacher- (worksheet-) driven strategy to an open-ended learner-driven strategy [31]. In one form of the teacher-driven strategy (confirmatory practical work), learners follow „recipes" in implementing procedures provided by the teacher, with limited thought and purpose [15]. This strategy has been criticised for not reflecting the work of professional scientists [32]. Thus, the strategies used in inquiry-based teaching and learning (in this case during practical work), have been considered to range only from teacher-directed structured and guided inquiry, to learner-directed open inquiry [33].

Instructional design models are useful when implementing IBPW. Although many of the models exist [e.g., 34, 35], the Science Laboratory Instructional Design (SLID) model [36] focuses on practical work. The phases of the SLID model are Initiation, Planning, Implementation, Evaluation, and Feedback. The implementation phase which occurs in the classroom can be carried out using an instructional model which as noted by the National Research Council [33], is useful when sequencing and organising inquiry-based learning experiences in the classroom. An example of the models is the engagement, exploration, explanation, elaboration, and evaluation (5e) instructional model [37]. Various scientific practices are involved in the 5e instructional model [38].

2.3. Personal domain: A framework of teacher competencies
Teacher competencies broadly consist of knowledge, understandings, skills, and values [39, 40]. Thus in the presented study, we extend the personal domain of the model in figure 1 to include skills and values. While skills include pedagogical, management, and personal skills, the values that teachers need include collaboration and teamwork; commitment and dedication to their practice; in addition to the desire for excellence, continuous learning, and innovation [39].

The knowledge base of teachers can be described using the Technological, Pedagogical, and Content Knowledge (TPACK) framework of Mishra and Koehler [41]. This knowledge framework is shown in figure 2. The two circles at the top of the figure reflect the first framework of teacher knowledge proposed by Shulman [42], who asserted that teachers need Pedagogical (P) and Content (C) Knowledge (K). This so called PCK concept, has been interpreted in several ways for different purposes in science education research [43], although the PCK model of Magnusson, Krajcik [44] has been predominantly used.

According to this PCK model, science teachers require knowledge of context, Content Knowledge (CK), Pedagogical Knowledge (PK), and Pedagogical Content Knowledge (PCK). As an example, CK includes the actual (science) subject matter to be taught [41], in addition to knowledge of scientific and classroom inquiry [33]. Also, the PCK domain has five components consisting of Orientation towards science teaching; Knowledge and beliefs about the science curriculum; Knowledge of instructional approaches; Knowledge and beliefs about the understandings of science learners; and Knowledge and beliefs about the assessment of learning.

Following the introduction of technology in education, Mishra and Koehler [41] expanded the PCK concept with the addition of Technological Knowledge (TK). TK is knowledge about standard technologies (such as books), in addition to more advanced technologies (including interactive computer simulations and data loggers). Reformers and researchers [including 45] advocate the coupling of simulations and/or other technological tools with hands-on practical investigations in order to enable learners to better understand essential concepts in science. That being said, the addition of technology resulted in the full TPACK knowledge framework shown in figure 2. The framework incorporates four new domains of teacher knowledge consisting of Technological Knowledge (TK), Technological Content Knowledge (TCK), Technological Pedagogical Knowledge (TPK), and Technological Pedagogical Content Knowledge (TPACK). A full description of the TPACK framework is readily available in the related literature [including 41, 46]. The preceding discussion of the personal domain of the model in figure 1 provides a basis for identifying gaps in the competencies of teachers in relation to the implementation of IBPW.

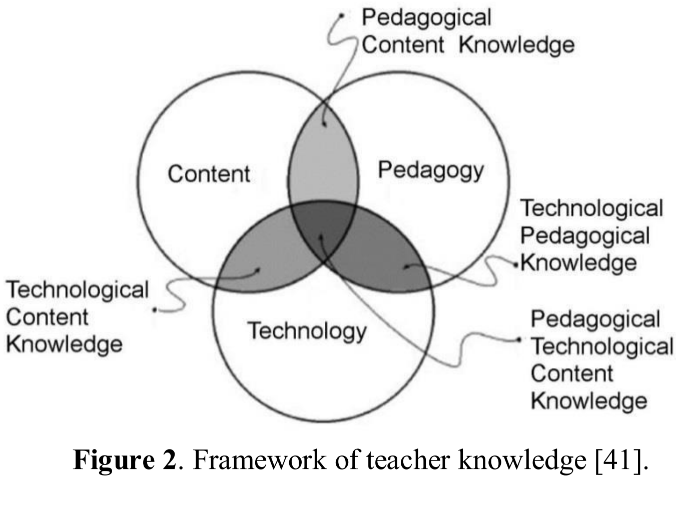

Figure 2. Framework of teacher knowledge [41].

3. Methodology

3.1. Introduction

The presented study was carried out in the north-eastern South African province of Gauteng. Though this is the most urbanized province in the country [47], in 2011, the percentage of non-fee paying public schools in the province was 73.4 [48].

In the data collection, we used a case study research strategy involving two resource-constrained high schools (School O and School P). The schools belonged to the Electronic Schools Project that the South African Department of Education was piloting in the province of Gauteng. The project involved seven high schools in which the government deployed computer technology for teaching and learning. The technology included interactive whiteboards (Smart Boards), tablet computers for all learners, and Internet access. The selection of the two schools was based on the income level of the surrounding community (non-fee paying schools) and the grades offered (high school grades). Physical sciences (integrated physics and chemistry) are taught in high school in Grades 10, 11, and 12.

The principals of School O and P consented to the participation of their respective schools in the presented study. In addition, all six of their physical sciences teachers (two in School O and four in School P), in addition to the demonstrator in School P, provided informed consent to voluntarily participate in the data collection. The consent was based on the principles of safety in participation, trust, and privacy. The participating educators all had a degree in education or a teaching diploma. We used all six high school classrooms being taught by these educators in the data collection. The average class size was forty.

3.2. The data collection

In this regard, the techniques used over a period of six weeks consisted of interviews, classroom observation, field notes, and artefacts.

3.2.1. Classroom observation, field notes, and artefacts. Five of the six physical sciences teachers were observed in the classroom during practical work, with eight lessons observed in total. The observed practical lessons covered phenomena that are physical (such as electrical conductivity) or chemical (e.g., endothermic reactions). The observations were carried out with the help of an observation protocol. The protocol contained open-ended items for examining teacher competencies in relation to IBPW. Three examples of the items are:

0) Topic of practical work - topic of lesson taught before practical work - and topic of lesson scheduled after practical work- .
1c) What is the nature of the simulation (if involved)? (e.g., interactive/a passive demonstration and how it reflects the real world).
2) What is the intended learning outcome as specified to learners (orally or in written form)?

Item 0) allows the role (confirmatory or not) of the practical lesson to be determined. That is, whether the practical work is used in concept development or not. This is indicative of quality of the PCK of the teacher, for example. Item 1c) grants access to the state of the PK of a teacher in relation to instructional planning. Item 2) provides evidence of whether a goal was set in the initiation phase of practical work while also further revealing the PCK quality.

In addition to observing the practical lessons as per the observation protocol, the first author (F V Akuma), also collected the worksheet (artefacts) used in the classroom. Outside the classroom, this author spent at least eight hours per week in the office or science laboratory with participating teachers. This allowed data about the practical work being prepared by participants to be gathered. Also recorded were new lesson arrangements. The data gathered in this way was kept as detailed field notes.

3.2.2. Interviews. The six physical sciences teachers in Schools O and P, in addition to the demonstrator in School P, participated in individual interviews following the data collection using the techniques in 3.2.1. There was an interview protocol for the teachers and another for the demonstrator. Though with a difference mentioned subsequently, both protocols were developed to suit the purpose of this study and were semi-structured. The interview protocol for the teachers contained twelve items. Two examples of the items follow:

2) Tell me what you consider when designing or selecting practical work exercises so that learners can learn best.
7) Some people believe that learners" prior knowledge and experiences are sufficient in the beginning of practical work. What is your opinion?

Item 2) is useful in uncovering the knowledge of a teacher regarding the Initiation and Planning phases of IBPW. This includes the selection of a practical work strategy and the preparation of suitable learning experiences. Item 7) can reveal the knowledge of a teacher regarding the sequencing and implementation of IBPW.

The interview protocol for the demonstrator was designed to gather data not about the competencies of the demonstrator regarding the implementation of IBPW, but rather about the competencies of the physical sciences teachers of School P in this regard. This is exemplified in the following item: 9) Tell me how these teachers usually use interactive computer simulations (simulated equipment) during practical work? With this item, we can gather data on whether participating teachers are using interactive simulations, for example, in an inquiry-based manner (e.g., in conceptual development), in concept verification, or in passive demonstrations. This data is indicative of the state of a teacher's TPK in relation to practical work. The interviews which lasted about half an hour each, were audio recorded, then fully transcribed before being made available to participants for verification.

In sum, data was collected on several occasions over an extended period of time, using multiple sources and techniques. This increased the credibility and trustworthiness of the study results [see e.g., 49].

3.3. Data analysis

We started by identifying individual gaps in the competencies of participants regarding the implementation of IBPW. The identification was in relation to the contents of section 2.3. Four examples of the gaps from different data sources are contained in the first column of table 1.

In order to proceed in the data analysis, we used the data-driven inductive approach in thematic analysis [50], coupled with the method of constant comparison [51]. Thus, each newly identified individual gap in competencies was compared with the previously identified gaps in order to find similarities and differences in the gaps. The first two individual gaps in table 1 are similar as gaps in Pedagogical Knowledge. This is indicated in the second column of the table. However, each of the first two individual gaps in competencies is different from the last two in the first column of the table. These last two gaps are examples of gaps in Content Knowledge and Technological Knowledge respectively, as indicated in the second column of the table. In this manner, gaps could be identified in the competencies of participating physical sciences teachers in different aspects of the framework of teacher competencies earlier discussed in section 2.3.

Table 1. Examples of individual gaps in competencies and related categories.

Individual gap	Category
"What I actually do before a practical [practical work session]… I teach them… the theory… Now, they got the prior knowledge."	Pedagogical Knowledge
Worksheet did not require that learners draw their experimental setup until at the end of the worksheet	
Teacher O2 expressed uncertainty about which rule is used to determine the direction of the induced current in a wire coil	Content Knowledge
Inability to access PhET simulations through the Smart Board	Technological Knowledge

4. Results

In presenting the results, we have in some cases used the exact words of participants. In this regard, it is useful to bear in mind that the term "practical" is used as slang by some participants to refer to practical work.

4.1. Gap in CK

During an informal conversation as per the field notes, Teacher O2 expressed uncertainty about which rule is used to determine the direction of the induced current in a wire coil. On a separate occasion, the same teacher expressed difficulties in explaining Faraday's law and following a discussion of the law; the teacher asked whether the researcher could teach this law to her learners.

4.2. Gap in PK

Based on the worksheets of the three practical lessons observed in School O, the teachers did not leave gaps in the experimental procedure for learners to complete. Also, the worksheets for both practical lessons observed in the case of Teacher O2, did not allow learners to draw the experimental setup, while the worksheet provided by Teacher O1 did not require that learners draw their experimental setup until towards the end of the worksheet. This is in addition to not asking learners to write down their hypothesis until after completing the results table. That being said, the omission of the experimental setup on worksheets and the presence of gaps in the experimental procedure were not mentioned by both teachers of this school when interviewed on what they consider when designing or selecting practical exercises. That said, Teacher P4 had an incorrect concept of prior knowledge, as evidenced in the following statement: "What I actually do before a practical… I teach them… the theory… Now, they got the prior knowledge." A gap in PK is also reflected in the opinion of Teacher P2, who noted that learners need support during practical work only if they were poorly prepared by their teacher.

4.3. Gap in TK

When interviewed about the accessibility of interactive computer simulations, Teacher O2 responded by saying "I don't know where to get them. The one that I am using right now, someone from (name of university) came with … I can't get something new…" Similarly, Teacher O1 noted an inability to access PhET simulations through the Smart Board, due to an inability to load the simulations on the device. In line with the above interview results, the use of interactive computer simulations in practical work was not observed for both teachers. While answering an interview question about interactive computer simulations, Teacher P3 referred to a temperature probe (data logger) as a computer simulation. The teacher also referred to temperature probes as pH probes in the following words: "We just needed to have computer simulations, just to check the temperatures. Otherwise, with the pH probes that we have – the manual pH probes – we cannot." Also, when asked to comment on the competencies of physical sciences teachers of School P in terms of selecting appropriate interactive computer simulations for use in practical work, the demonstrator said the following: "… [E]ducators seem not to be too friendly to the use of computers and as such you see that simulations which might help … are not done …" This statement is supported by observation data which shows that none of the five practical lessons observed in School P involved interactive computer simulations.

4.4. Gap in TPK

In relation to the selection of interactive computer simulations, Teacher P1 noted that the selected simulation has to be "so simple and understandable" and "it has to validate a theory [i.e., verify content taught earlier]". The kind of computer simulation this teacher has in mind is seemingly not one that promotes IBPW. Also, all four teachers of School P found interactive computer simulations useful only in one of the following situations: when hands-on equipment is lacking, when faced with an invisible phenomenon, when conventional equipment is hazardous, and when involved in concept development. That being said, Teacher O2 considers hands-on SEEMs as always superior to interactive computer simulations. Additionally, when asked during the interview about her use of interactive computer simulations, this teacher stated: “I just teach first the topic, then after that, I show them what I was teaching – how it happens – using the computer simulation”. Moreover, during an informal conversation as recorded in the field notes, Teacher O1 admitted to not being familiar with ticker-tape experiments. She also asked the researcher to rather teach the practical lesson involving the use of this device. While this was not possible on methodological grounds (as a pre-intervention study), the teacher ended up cancelling the practical lesson, citing lack of access to the laboratory as the reason for the cancellation.

4.5. Gap in professional values
In School O, Teacher O2 cancelled a task in one of her practical lessons because resistors could not be located when they were to be given to learners. In relation to School P, an excerpt from the field notes reads as follows. “Though science equipment is stored in this room [science laboratory turned office], since using the room for the fourth time now (each time so far, for about four hours), I am still to see a science teacher taking equipment to class, or returning with any from class”. However, this observation does not cover one of the four participating physical sciences teachers of School P, as his desk is found in a different office. When asked in an interview about the quality of practical activities selected or designed by physical sciences teachers at School P, the demonstrator noted that:

> [Y]ou would find that the teachers can only do the practical work if it‟s a school-based assessment task from the department of education… for the whole year they can just do three…So in as much as they [practical lessons] would be helpful, they are not done to the satisfaction of what the learning programme requires.

These inadequacies are linked to such professional values as dedication to practice and the desire for excellence.

5. Discussion and Conclusion

The purpose of the presented research was to identify gaps in the competencies of participating physical sciences teachers. This is in the implementation Inquiry-Based Practical Work (IBPW), the strategy that these teachers would have been experimenting with in the domain of practice of the Interconnected Model of Teacher‟s Professional Growth (figure 1). In relation to the personal domain of the model and the TPACK framework (figure 2), the results show that the gaps lie in the domains of values, PK, CK, TK, and TPK. Although there has been much research on various aspects of the PCK of science teachers [including 52], studies about gaps in the competencies of physical sciences teachers in relation to IBPW are scarce in the science education research literature.

The presented results are significant in relation research and practice regarding the implementation of IBPW. In the latter regard, and contrary to the opinion of Teacher P2 that learners need support during practical work only if they were poorly prepared by their teacher, Zion, Cohen [53] noted the importance of not only support, but also facilitation and supervision during inquiry-based learning. Also, regarding not asking learners to write down their hypothesis until after completing the results table (Teacher O1), Klahr and Dunbar [54] noted that hypothesising comes in the beginning of problem-solving (which is involved in directed and open inquiry). Thus, the results of the presented study point to the need for further Professional Development (PD) in the implementation of IBPW. This is in line with Dudu [55] who recommended the PD of South African physical sciences teachers in inquiry-based teaching and learning. This study informs the implementation of this broad recommendation in the specific context of practical work. An enhanced understanding of the aspects for which the most support is required, can assist in focusing

PD resources more effectively and efficiently [56]. In this regard, the presented study has identified the gaps in teacher competencies linked to the implementation of IBPW that could be incorporated in the PD of participating physical sciences teachers. A strong effort in science teacher PD is needed, in order to (ultimately) sustain the passion for science among young people and to prepare a workforce adequate for today's knowledge- based societies [8]. Based on the Interconnected Model of Teacher's Professional Growth (figure 2), the incorporation of elements of the external domain coupled with enactment and reflection in such a PD effort, could yield gains in the required PK, TPK, CK, TK, and values, in the domain of consequence.

While the practice-based implications of the presented research are contained in the preceding paragraph, there is also a research-based implication. The research-based implication lies in the fact that though practical work is inadequately implemented in physical sciences classrooms in communities of low socio-economic status in South Africa and beyond, the results of this in-depth study are not necessarily applicable to other such classrooms. Due to this limitation, research along similar lines might be needed in other physical sciences classrooms in communities of low socio-economic status in South Africa and elsewhere. We see that in order to better support IBPW in the physical sciences in South African and other schools in communities of low socio-economic status, the efforts of both researchers and PD providers would be needed. The efforts are worthy if we consider the point put forth by Nompula [16] that some learners have restricted access or fewer opportunities to engage in inquiry-based science education due to their teachers having inadequate relevant skills and knowledge in the implementation of such lessons. That being said, the required efforts will increase learner access to IBPW, a vehicle for enhancing understanding while sustaining and developing learner interest in science, in the service of future scientific research and economic development.

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