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Revealing the Structural Complexity of Component Interactions of Topic-Specific PCK when Planning to Teach

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Abstract Teaching pedagogical content knowledge (PCK) at a topic-specific level requires clarity on the content-specific nature of the components employed, as well as the specific features that bring about the desirable depth in teacher explanations. Such understanding is often hazy; yet, it influences the nature of teacher tasks and learning opportunities afforded to pre-service teachers in a teaching program. The purpose of this study was twofold: firstly, to illuminate the emerging complexity when content-specific components of PCK interact when planning to teach a chemistry topic; and secondly, to identify the kinds of teacher tasks that promote the emergence of such complexity. Data collected were content representations (CoRes) in chemical equilibrium accompanied by expanded lesson outlines from 15 pre-service teachers in their final year of study towards a first degree in teaching (B Ed). The analysis involved extraction of episodes that exhibited component interaction by using a qualitative in-depth analysis method. The results revealed the structure in which the components of PCK in a topic interact among each other to be linear, interwoven, or a combination of the two. The interwoven interactions contained multiple components that connected explanations on different aspects of a concept, all working in a complementary manner. The most sophisticated component interactions emerged from teacher tasks on descriptions of a lesson sequence and a summary of a lesson. Recommendations in this study highlight core practices for making pedagogical transformation of topic content knowledge more accessible.

Keywords Topic-specific pedagogical content knowledge · Component interactions · Chemical equilibrium · Pre-service teachers · Transformation of content knowledge

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Introduction

Teaching pedagogical content knowledge (PCK) to science pre-service teachers (PSTs) is an intricate process. One reason is the realization that it is no longer sufficient to refer to PCK without distinguishing its level of location. The multidimensional nature of PCK as teachers' germane professional knowledge is widely acknowledged in the literature (e.g., Nezvalová 2011; Veal and MaKinster 1999). These authors have proposed PCK taxonomies to help in visualization of the different levels of PCK. In their explanations, they suggest the existence of PCK at a discipline level as in science, at a domain level as in chemistry, and at a topic level as in chemical equilibrium. This multidimensional nature was a welcomed engagement in the recent PCK Summit II. The summit acknowledged the PCK taxonomy in the newly Refined Consensus Model (RCM) of PCK. The RCM of PCK reflects discipline, topic, and lastly concept-specific PCK as the grain sizes in a continuum that is found in each of the three developmental realms of PCK called collective PCK (cPCK), personal PCK (pPCK), and enacted PCK (ePCK) (Carlson and Daehler 2018). The challenge still facing the PCK community, however, is the conceptualization of these three grain sizes of PCK in a manner that distinguishes them from each other. Furthermore, questions about the relationship between them are yet to be asked and resolved. Nonetheless, understanding PCK in the abovementioned manner helps us to understand that we require different knowledge to teach science from other disciplines, and similarly to teach different topics within the discipline (Abell 2008). Widely shared recommendations in the science education literature is to support the development of PCK with reference to specific topics (Abell 2008) and to consider use of such knowledge a core practice to be passed on to prospective teachers (Aydin et al. 2015). Despite this shared understanding, the teaching of PCK in specific topics to PSTs has, however, remained obscure. Partly due to the lack of clarity on the type of components to be used when PSTs are learning to develop PCK in science vs. PCK within specific topics. It is exactly at this point that the fog and ambiguity set in. Often, the slip lies in failing to recognize PCK in topics as a version of PCK that is content specific, thus to be defined and interpreted from components that are content specific. This study aims to illuminate the use of content-specific components in implementing PCK in a specific topic and expose the resulting complexity in the structural arrangement when transformation of content knowledge is considered in the planning well-reasoned lesson.

The Challenge

Two different schools of thought are found in the literature about implementing PCK in topics. The first is a set of studies using a version of PCK defined at a discipline level, and the indication of the topic explored in the study appears to be the only connection to PCK in a topic as construct. In such cases, the components of PCK are drawn from the layer of generic teacher knowledge bases found in the Teacher Professional Knowledge and Skill (TPK&S) model, the consensus model of PCK (Gess-Newsome 2015). These include *pedagogical knowledge*, *curricular knowledge*, *assessment knowledge*, etc. Studies that employed the widely used model in science by Magnusson et al. (1999) would also fall into this category (e.g., Karal and Alev 2016; Aydin et al. 2015). The second school of thought is seen in studies where both the topic of interest and the conceptualization of PCK at a topic level, different to discipline level, have been explicitly communicated. In such cases, content-specific components have been used to conceptualize PCK in topics as a construct different to discipline-based PCK by scope of focus. Such components are drawn from the topic-specific professional knowledge (TSPK) layer of the consensus PCK model such as *knowledge of students*, *representations*, and *conceptual teaching strategies*. Examples of studies that fall into this category are (e.g., Davidowitz and Potgieter 2016; Witzig and Sickel 2017). These studies include all the content-specific components used in defining PCK in topics in their research design. The two different approaches outlined here are but one example, reflecting the fuzziness in the operationalization of PCK within topics in science education. The question to be asked is, does it matter? According to Sanger (2008), the practice of teaching has a moral element inherently attached to it. One suggested way in which teacher educators could ensure moral salience in their classrooms is by having a clear sense of what they need to know (such as differentiating between discipline vs. topic-specific PCK) and be able to do. The same view is expressed by the core practice movement (McDonald et al. 2013) calling for disciplines to reflect and make explicit to PSTs the practices and pedagogies they consider the most essential to efficient teaching. So, given the agreement on the value of PCK within topics, the need for making explicit the operationalization of this specific construct is herein argued as a practice that should morally matter to science educators. Science teacher preparation programs are to demonstrate a clear understanding of the features that distinguish PCK within topics from other versions, and how those features bring about the learning of the desired pedagogical transformation of content of topics for the benefit of learners.

Theoretical Background

Defining the Topic-Specific Nature of PCK

This study acknowledges the earlier studies in the literature that brought the idea of topic-specific PCK into view. For example, Van Driel et al. (1998) examined the development of PCK of pre-service teachers in chemical equilibrium, while Park et al. (2010) investigated PCK in two life science topics photosynthesis and heredity. The findings from that study showed that teacher competence varied in the topics investigated. Another study on two chemistry topics (electrochemical cells and redox reactions) conducted by Aydin et al. (2014) identified components of discipline PCK that selectively revealed the topic-specific nature of PCK. These were found to be content specific, e.g., representations rather than discipline-generic components such as assessment. The influence of these studies is seen in a study that was built on the idea of topic-specific PCK and provided an operational definition and a model articulating the content-specific constituent components of PCK within topics (Mavhunga and Rollnick 2013). In that study, the topic-specific version of PCK has been termed topic-specific pedagogical content knowledge (TSPCK) comprised of five components that are content specific in nature. These are *learner prior knowledge*, *curricular saliency*, *what is difficult to understand*, *representations*, and *conceptual teaching strategies*. These components were proven to work together to demonstrate a valid theoretical construct (TSPCK) that is measurable (Mavhunga and Rollnick 2013). Similar to PCK (Park and Chen 2012), TSPCK component interactions are anticipated to be complex, however, yet to be empirically tested. As previously discussed, the aim of this study is not to promote the need for clarity. Thus, focus is placed on illuminating the complexity in the structural arrangement of TSPCK components when the content of a topic is pedagogically transformed in the planning of a well-reasoned lesson.

The understanding of such knowledge will have both a conceptual and a methodological benefit. Conceptually, the development of a clearer conception of what content-specific component interactions look like during pedagogical transformation of the content in a topic, may visually help us define sophisticated levels of TSPCK. From a methodological perspective, the understanding of the teacher tasks that promote the emergence of sophisticated component interactions would offer teacher educators insight into ways of constructing learning opportunities that promote the learning of sophisticated TSPCK.

The questions thus asked in this study are

1. How do the components of TSPCK relate to each other structurally in a context of planning to teach a chemistry topic such as chemical equilibrium? and
2. In what teacher tasks do the observed complex TSPCK component interactions emerge?

The Significance of Understanding Interactions Among TSPCK Components

Scholars of PCK advocate that teachers should have a firm understanding of all PCK components and, more importantly, their interactions. This understanding is needed particularly in order to effectively plan and deliver instruction for a certain group of students in a specific context, where teachers must be able to integrate those components in a coherent way (Loughran et al. 2006). A similar kind of understanding for the construct of TSPCK is thus argued. This places more emphasis on the need to, similarly, understand the components of TSPCK and their interactions.

The literature reveals several approaches used previously to understand the interactions of discipline PCK components. One approach explored is how a single component affects another component. For example, Cohen and Yarden's research (2009) has indicated that the teachers' lack of curricular knowledge of the topic of cells limited their use of instructional strategies. Another approach examined how a particular component relates to the whole construct of discipline PCK and practice, as in the study conducted by Schmelzing et al. (2013). It is reasonable to hold a view that a more holistic approach would be the exploration of all the components in a given PCK model.

Several studies employing this approach are known and are of interest to this study. One of these studies is the study by Park and Chen (2012), who used the pentagon model (Park and Oliver 2008) comprising of five components that were all considered in their study. The study found that the Knowledge of Students' Understanding in Science and Knowledge of Instructional Strategies and Representations were the most frequently integrated with any other component. A similar study was conducted by Aydin and colleagues (2015) using the

Magnusson et al.'s PCK model (1999). The authors investigated the PCK components' interaction on the topic of rates of reaction. Their findings indicated that PSTs registered development in all individual PCK components as well as in their interplay. However, the interaction between knowledge of assessment and instructional strategy was less visible and lacking. The value derived from these studies in the context of our discussion is acknowledged as usefully revealing: (i) the components of the broader discipline PCK that are visible in a topic and those that are not; and (ii) the strength of the visible component interactions as pre-service chemistry teachers learn to use their learned PCK. What remains as a gap in the literature is the understanding of the structural layout in which the TSPCK components interact, particularly in those interactions that reveal sophisticated TSPCK. It is argued here that such an understanding would also help the PCK community respond towards McDonald et al.'s. (2013) call for the science education discipline to identify and communicate openly the core practices associated with discipline and topic-specific PCK and the features that bring out sophistication in each construct.

Capturing and Portraying Component Interactions Revealing TSPCK

That teachers' knowledge of practice is tacit (Polanyi 1962; Rollnick 2017) even to teachers themselves has been repeatedly discussed. Teachers are generally unable to explicate their thinking about their teaching in the ways that expose the pedagogical reasoning underpinning their practice. As a consequence, efforts to uncover and capture teacher professional knowledge such as PCK have proven to be difficult (Cooper et al. 2015). This includes explicating the structural setup in which the components of TSPCK are formatted when used interactively. A tool known as content representations (CoRes) has proven to be a powerful tool for unpacking teachers PCK in many science studies (e.g., Hume and Berry 2010). The CoRes is comprised of a combination of Big Ideas and specific prompts that are explicit cues for discussing teaching within a given topic or theme. This combination assists teachers' to access aspects of content-specific pedagogical reasoning that helps provide insights into their tacit practices. According to Cooper et al. (2015), the value of CoRes as a data collection tool is in creating ways of making the teachers' thinking visible. CoRes could be used in conjunction with short narratives based on the teachers' accounts and reflections of teaching a specific science topic to particular groups of students (Loughran et al. 2016). These narratives are called PaP-eRs. CoRes have been widely used than PaP-eRs in many different ways by different groups of researchers. For example, teachers have adopted them as a tool for planning of the science curriculum and unit of teaching (Lehane and Bertram 2016). Science educators have used CoRes as a tool in a pre-service program for organizing and pulling together generated thinking as PSTs learn TSPCK in a given topic (Mavhunga and Rollnick 2017). They have also been used in promoting the PCK development of university educators (Garritz and Ortega-Villar 2012). In this study, CoRes are employed as a tool to capture and portray the developing TSPCK of chemistry PSTs, exposing the layout in which component interactions are structured particularly in segments that display sophisticated TSPCK. In this study, particular focus was placed on the prompt of "suggested conceptual teaching strategies" where PSTs provided their reasoned teaching strategies. They were given an opportunity to expand in detail on their suggested strategies in the form of detailed lesson plans as explained in the “Method” section that follows.

Method

The study employed a qualitative in-depth analysis method for analyzing explicit TSPCK (Park and Oliver 2008). It was located in the chemistry methodology course with 15 PSTs, who were in their final year of the four-year undergraduate teacher qualification degree (B Ed). The objective of the course was to improve the quality of PCK in core chemistry and physics topics, one of which is chemical equilibrium. Chemical equilibrium was chosen because of perceived difficulty, in understanding and being abstract in nature; yet, it contains the foundational understanding needed in other chemistry areas (Bergquist and Heikkinen 1990). The development of PCK in chemical equilibrium was based on an intervention that entailed learning the competence to pedagogically transform content knowledge by reasoning through the five content-specific components of TSPCK.

The Intervention

The intervention was over a period of 6 weeks. Each week had three, 1-h periods used as a combination of a lecture and tutorial work. The emphasis in the intervention was in learning how to transform content knowledge by reasoning and analyzing concepts of chemical equilibrium through the content-specific components of TSPCK. The five content-specific components of TSPCK were introduced one at a time, developing their meaning as well as their interactive use in formulating conceptual explanations. CoRes were used as a tool to capture and organize thoughts for teaching a topic resulting from reasoning through the components of TSPCK, as guided by the prompts of the CoRes. Content concepts of chemical equilibrium that naturally linked to each component of TSPCK were discussed. For example, the component of the learners’ prior knowledge includes knowledge of well-known learner misconceptions in a topic, e.g., the misunderstanding of the concept of *dynamic chemical equilibrium*, in particular, that the concentration of the substances in a reaction at chemical equilibrium is equal. Table 1 provides a summary of the sequence of introduction of TSPCK components and their links to relevant concepts of chemical equilibrium with examples of the activities performed.

Data Collection

The data collected consisted of 15 individually completed CoRes coupled with expanded lesson plans on the topic of chemical equilibrium. The expanded lesson plans were semi-structured and open ended to allow PSTs to write their suggested conceptual teaching strategies for a Big Idea mentioned in the CoRes, more explicitly and in detail. The expanded lesson plan had a structure with headings such as *conceptual teaching strategy to be used*, *resources needed*, *duration*, *sequence to be followed*, and *summary of most important content*. These headings were associated with typical teacher tasks associated with planning for teaching. They served as guiding sub-titles for PSTs to provide a detailed description of the conceptual teaching strategy suggested in their CoRes for each Big Idea. Both the CoRes and the corresponding expanded lesson plans were completed at the end of the intervention as part of a major

Table 1 Description of the topic-specific PCK interventions by component

Component	Intervention	Class activity
Learners' prior knowledge	Discussions were on widely researched common misconceptions on the topic found in the literature. Discussions were followed by a presentation of recommended, published teaching strategies to correct common misconceptions. Content concepts covered were conditions for dynamic chemical equilibrium.	A video clip showing the changing equilibrium point of the NO/N_2O_4 system with temperature was shown to the class. A question on a common learner misconception, whether the concentrations at equilibrium are equal was posed. This activity was a whole class discussion with probing questions.
Curricular saliency	Discussion geared towards identifying the "big ideas" and the corresponding subordinate concepts in a topic as suggested by Loughran et al. (2006). This was followed by a discussion on sequencing the identified big ideas to scaffold learning: awareness of the concepts needed before teaching the topic and knowing what is most important to understand within each Big Idea were discussed. Concepts covered were dynamic chemical equilibrium; factors disturbing equilibrium and the equilibrium constant.	In permanent groups of four, PSTs developed a concept map on the topic. They were allowed to access any other resources they needed, e.g., text books, curriculum plans. They were to provide rationale for their suggested maps. Part 2 of the activity was to convert the main concepts in the suggested concept maps into statements of meaning (Big Ideas) and re-arrange their concepts maps such that the suggested Big Ideas are in sequence, showing prior concepts and linked to subordinate concepts with explanatory notes.
What is difficult to understand	Exploration of concepts considered difficult to learn, and identifying the actual issues that make understanding difficult. This was more than settling on the abstractness of concepts but pin pointing the actual difficulty. Concepts covered were reversible reactions in a state of chemical equilibrium.	In the same groups, PSTs were asked to share from their experience as learners and from their own teaching of the topic during school experience, what they considered difficult for learners to understand and, in turn, what they found difficult to teach.
Knowledge of representations	Introduction of the three levels of explanations in chemistry which are the macroscopic, symbolic, and sub-microscopic level. Emphasis was placed in the power of using all three representations side by side in explaining a phenomenon.	PSTs were asked to explain dynamic equilibrium using representations (at all three levels including the sub-microscopic level) of the same example - the NO/N_2O_4 reaction at room temperature discussed earlier under Learner prior knowledge.
Conceptual teaching strategies	Emphasis was placed on conceptual teaching strategies rather than general pedagogy and logistics. A conceptual teaching strategy would consider the other four TSPCK components in its presentation.	In the same groups, PSTs practised to develop lessons plans showing deliberate consideration of the knowledge generated from the other four TSPCK components.

assignment in the methodology course. Additional data in the form of observation notes and submitted responses to short class tutorials and activities were collected during the course. The additional data were used in constructing a detailed description of the intervention.

Analysis

Data from all 15 participants were analyzed using the qualitative in-depth analysis method for explicit TSPCK (Park and Chen 2012). According to this approach, the interactive presence of two or more components of TSPCK demonstrated in a segment of a CoRes or the expanded lesson plan was first identified and labeled as a "TSPCK episode." A planning document such as a CoRes or a lesson plan may have a few specific portions where the provided descriptions contain a TSPCK episode. An example of a segment that contained a TSPCK episode is demonstrated as follows.

> "I will first explain the concept of a closed and open system, indicate how a state of equilibrium is established in a closed system, by writing an equation down, for example $N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$. I will explain the importance of the double arrow pointing in opposite directions so as to show that the chemical reaction is reversible. I will make learners aware that the reversible reactions do not go to completion. I will also point out the importance of the phases of the reactants and products in the equation."

This extract was taken from a PST's expanded lesson plan, under the heading "Sequence to be followed in a lesson." Sequencing of a lesson is regarded as a task when planning a lesson. The expanded lesson was based on the conceptual teaching strategy suggested for the Big Idea "Chemical Equilibrium is dynamic in nature" contained in the PST's completed CoRes. TSPCK episodes were more visible in the expanded lesson plans by virtue of the nature of expanded description. The extract shown previously contains a TSPCK episode, as it reflects considerations of knowledge about teaching the topic from more than two TSPCK components. The first component presented is that of curricular saliency, evident from the consideration of pre-concepts such as *closed* and *open systems*. The second component is representations evident from the use of symbolic equations with emphasis of the features that count most such as the explicit mentioning of the double arrow. A third component is referred to by the presence of the statement on reversible reactions that do not go to completion. The fact that reversible reactions in a chemical equilibrium do not go to completion is an aspect considered difficult for learners to understand. A possible reason could be apportioned to the manner in which reversible reactions are commonly introduced as reactions that go to completion in one direction and may require a change of conditions to go in reverse. Thus, reference to reversible reactions not going to completion in the extracted segment, signals the component of "what is difficult to understand." The component of curricular saliency is repeated in the extracted segment by bringing anew the needed awareness of the state of phases of the reactants and products in a reaction at equilibrium. Learners commonly overlook the importance of the states and to include both solids and liquids when calculating Kc (Quilez-Pardo and Solaz-Portolez 1995). The discussion on Kc was not part of this lesson, but the effort of the PST to plan to prime learners ahead of the discussion of the concept was highly noted as avoiding a potential learner misconception (LP). Once identified, each TSPCK episode was then described in detail in terms of (i) what the pre-service teacher had written, (ii) what components are at play, (iii) what structural layout is depicted by the manner the components relate to each other, and (iv) the nature of teacher tasks in which the TSPCK episode emerged. The completed analysis of the identified TSPCK episode was then pictorially presented as a *TSPCK MAP*, adapted from Park and Chen (2012). A TSPCK MAP was defined as a pictorial diagram describing connections between components identified in a TSPCK episode (see Fig. 1). Three raters assisted in the verification of TSPCK episodes and in the ensuing analysis following a discussion and practice in the rules for coding.

How TSPCK Episodes Were Coded and Analyzed

As the purpose of this study was to illuminate the structural arrangements displayed by component interactions within TSPCK episodes, particular attention was placed on capturing

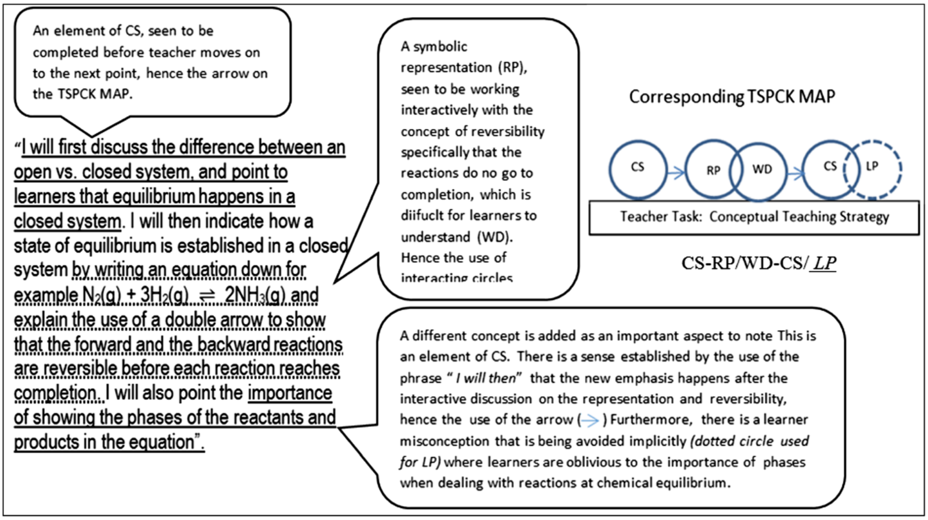


Fig. 1 An example of an extract from PST Zen coded and translated into a TSPCK MAP

and portraying evidence of the structure in which the visible component interactions are set. For purposes of simplicity, the components of TSPCK were abbreviated as follows: learner prior knowledge = LP; curricular saliency = CS; what is difficult to understand = WD; representations = RP; and conceptual teaching strategies = CTS. Figure 1 provides an example of a TSPCK MAP derived from the extract given as an example previously, given here also for purposes of demonstrating the rules used for coding.

In this map, there are four different components of TSPCK with one component repeated; curricular saliency (CS), representations (RP), what is difficult to understand (WD), and learner prior knowledge (LP). Solid circular lines around each component were used to indicate clearly distinguishable components of TSPCK found in a TSPCK episode. Where it was evident that the presence of a component was implied, a dotted circular line was used, as in the example of the LP component in Fig. 1. Where components were found to be inseparable and interlinking, they were then presented as overlapping circles. In cases where components were found to have a distinguishable linear sequence, they were represented with a solid linear arrow line pointing out the sequence in which the components had emerged in a TSPCK episode. The platform on which the identified components stand, indicates the type of the specific teacher task from which the TSPCK episode emerged. For example, the TSPCK MAP shown in Fig. 1 was interpreted to mean that the observed TSPCK episode emerged from a response explaining the conceptual teaching strategy to be used. The component of CS emerged as the first TSPCK component at the beginning of the episode. It appears to have been dealt with completely before moving on into a discussion that interwove the components of RP and an aspect that is difficult to understand (WD). This discussion was completed before the next concept deemed important (CS) was also interwoven in a discussion that aimed at avoiding a potential common learner misconception (LP) without explicitly mentioning it.

For purposes of ease in referring to a specific sequence displayed in a visualized TSPCK Map, a shorthand called "TSPCK Sequence" was invented. In a TSPCK Sequence, the components that emerged following each other in a linear sequence were represented by a dash (–), while interwoven component interactions were represented by a forward slash (/).

The implied TSPCK component, represented as a dotted circle in the TSPCK MAP, was shown underlined in italics. For example, the TSPCK Sequence displayed in the TSPCK MAP in Fig. 1, as examplar, was written out as CS-RP/WD-CS/ *LP*. The three raters practiced the rules several times until all were confident. They compared their analysis for each TSPCK episode identified and highlighted cases of difference in rating. Differences in each case were discussed until agreement was reached. The inter-rater reliability on the first-time agreements was calculated at a Cohen's kappa value of 0.85, which is considered acceptable.

Results

Thirty TSPCK episodes were identified across the CoRes and the corresponding expanded lesson plans collected from the total sample. Their descriptions are provided in the form of TSPCK sequences per participant in Table 2.

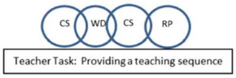
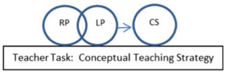
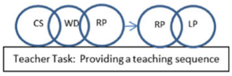
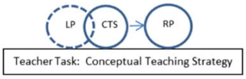
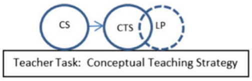
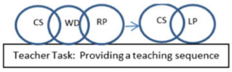
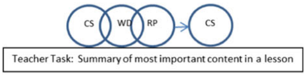
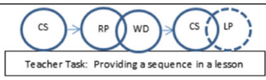
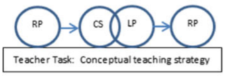
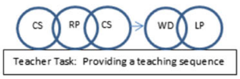
The TSPCK sequences in Table 2 indicate a myriad of combinations in which the components interact in the identified TSPCK episodes. TSPCK sequences that contained a high number of different and/or repeating components were generally regarded as reflecting sophisticated TSPCK. These were sampled for a detailed discussion (Table 3).

The findings confirmed anticipated understanding as well as revealing new understandings about TSPCK component interactions. What was confirmed, similar to PCK, the content-specific

Table 2 TSPCK episodes identified for each participant

Participant	Quantity	TSPCK Sequence	Nature of teacher task
Khaya	4	CS/WD/CS/RP	Summary of most important content knowledge in a lesson
		CS/WD/RP-RP/LP	Teaching sequence in a lesson
		RP/LP-CS	Conceptual teaching strategy
		LP/CTS/RP	Conceptual teaching strategy
Mimi	4	CS-RP/CS/*LP*	Conceptual teaching strategy
		CS-RP/WD (3)	Conceptual teaching strategy
Phumi	3	CS/WD/RP	Teaching sequence in a lesson
		CS-RP/WD (2)	Conceptual teaching strategy
Ben	2	CS/WD/RP-CS/LP	Teaching sequence in a lesson
		CS/CS/LP/RP	Summary of most important content knowledge in a lesson
Thami	2	CS-LP/RP	Conceptual teaching strategy
		CS/WD/RP-RP/LP	Teaching sequence in a lesson
Sipho	2	CS-CTS/*LP*	Conceptual teaching strategy
		CS-RP/WD	Conceptual teaching strategy
Lebo	2	RP-CS/LP	Conceptual teaching strategy
		CS-LP/RP	Conceptual teaching strategy
Shoni	2	CS-RP/WD	Conceptual teaching strategy
Zen	2	CS/WD/RP-CS	Summary of most important content knowledge in a lesson
		CS-RP/WD-CS/*LP*	Teaching sequence in a lesson
Nhleko	1	CS-RP/WD	Conceptual teaching strategy
Nduna	1	RP-CS/LP-RP	Summary of most important content knowledge in a lesson
Qondi	1	CS-LP/RP	Conceptual teaching strategy
Themba	1	CS/WD/LP/RP	Summary of most important content knowledge in a lesson
Noli	1	CS-WD-RP/CS	Summary of most important content knowledge in a lesson
Hloni	1	CS/RP/CS-WD/LP	Teaching sequence in a lesson

Table 3 Sample TSPCK MAPs for observed sophisticated TSPCK component interactions

Participant	TSPCK Sequence	TSPCK MAP	Nature of teacher task
Khaya	CS/WD/CS/RP		Summary of most important content knowledge in a lesson
	RP/LP-CS		Teaching sequence in a lesson
	CS/WD/RP-RP/LP		Conceptual Teaching strategy
	LP/CTS/RP		Conceptual Teaching strategy
Sipho	CS-CTS/*LP*		Conceptual Teaching strategy
Ben	CS/WD/RP-CS/LP		Teaching sequence in a lesson
Zen	CS/WD/ RP-CS CS-RP/WD-CS/*LP*		Summary of most important content knowledge in a lesson
			Teaching sequence in a lesson
Nduna	RP-CS/LP-RP		Conceptual Teaching strategy
Hloni	CS/RP/CS-WD/LP		Teaching sequence in a lesson

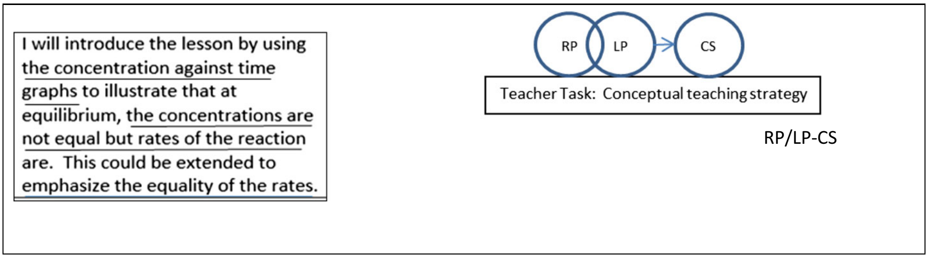


Fig. 2 Khaya's three-component TSPCK episode with explicit components

components of TSPCK interacted among each other in a variety of combinations that appeared to be complex and idiosyncratic (Aydin et al. 2014). The new revelations in this study are that the component interactions were distinguishable in structural formats. Observed structural formats were either an interwoven formation or a combination of a linear and interwoven formation co-existing in a TSPCK episode. Furthermore, the more complex component interactions seem to emerge from specific kinds of teacher tasks. Both the confirmed and the new findings are discussed in detail in the findings.

Findings Confirming the Anticipated Nature of TSPCK Component Interactions

The TSPCK sequences that are presented in Table 2 point to TSPCK component interactions that are complex and idiosyncratic. Individual PSTs displayed in their planning for teaching chemical equilibrium, sets of TSPCK episodes with unique permutations of component interactions that show little similarity to each other. The generated component interactions differed by the type of component present, the quantity and in some cases, same components repeated, and lastly by the structural arrangement in which the individual components emerge in a TSPCK episode. An example of this is seen in the four different TSPCK episodes generated by Khaya are shown as TSPCK sequences in Table 2 and as pictorial TSPCK Maps in Table 3. It is noted that three out of four TSPCK episodes have three components of TSPCK interacting, expressed in the TSPCK sequences: "RP/LP-CS," "*LP*/CTS/RP," and "CS/WD/CS/RP." While the three TSPCK episodes have the same quantity of components in an interaction, they, however, look different from each other. Figure 2 presents an extract of the planning segment from which the first episode RP/LP-CS emerged. In this planning segment, the pre-service teacher planned to begin the explanation using a

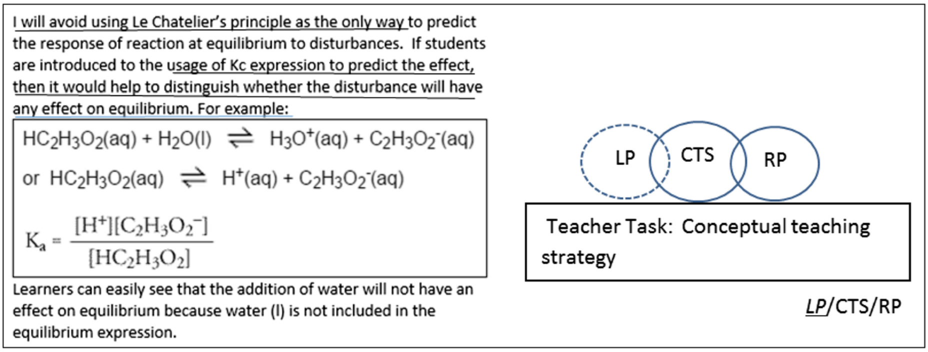


Fig. 3 Khaya's three-component TSPCK episode with an implicit component

"concentration-time" graph, which is regarded as a RP at a symbolic level. This specific representation seems to have been selected to provide an opportunity to explicitly address a particular common learner misconception (LP) as hinted in the extracted text; "…the concentrations are not equal, but the rates of reaction are." The discussion in this segment then proceeds to emphasize those aspects that are most important about the dynamic nature of chemical equilibrium. The act of emphasizing these core points, to be understood in a specified discussion, is an illustration of an understanding of the TSPCK component of CS, which requires a distinction and emphasis on important aspects to be learned. In this TSPCK episode, all three components of TSPCK are explicitly visible and distinguishable from each other.

Yet, when looking at Khaya's second TSPCK episode *LP*/CTS/RP in Fig. 3, the use of the component LP was implicit.

In this TSPCK episode, Khaya suggested a conceptual teaching strategy that addresses a particular common learner misconception about the learners' tendency to use the Le Chatelier's principle for the prediction of change in a chemical equilibrium, irrespective of the nature of the disturbance (Tyson et al. 1999). The misconception is implied, as shown by the extracted statement "I will **avoid** using the Le Chatelier's principle …", and the reader would have to be knowledgeable enough in teaching the topic to recognize the insight in this strategy. This observation makes this particular TSPCK episode of Khaya, particularly the way the component LP emerges, to be different from the previous three-component TSPCK episode and to others identified in his work.

A similar case, where the component LP is used implicitly, is noticed in the TSPCK episodes of Sipho CS-CTS/*LP* that are listed in Table 2 and are presented pictorially in Fig. 4. In Sipho's TSPCK episode, the common misconception about the disturbance of a chemical equilibrium due to an added substance is implied by the proposed conceptual teaching strategy, seen through the statement: "...use Le Chatelier's principle and the Kc expression interchangeably when determining the effects of disturbances on the equilibrium and not just one mechanism." The implicit emergence of a component in a TSPCK episode adds a layer of complexity to the variety in which components present themselves in TSPCK episodes.

In the cases mentioned, both Khaya's and Sipho's TSPCK episodes are structurally different from the others in the way the component of LP emerges; they also differ from each other by component composition; yet, both addressed the same common learner misconception and have three component episodes.

The third three-component TSPCK episode in Khaya's set is an episode with a TSPCK Sequence CS/WD/CS/RP, where one component of the CS is repeated in the sequence, as shown in Fig. 5. The extracted text contains a TSPCK episode where several important concepts of chemical equilibrium are enlisted. One of the important conditions needed for the state of equilibrium to occur is explicitly described in the opening sentence "Equilibrium can be established in a closed system". As mentioned earlier, the displayed understanding of pre-concepts and of the most important concepts is an element of CS.

The next sentence refers to a gatekeeping concept that is regarded as difficult to understand (WD), which concerns understanding the simultaneous aspect of reversible reaction. The component WD refers to those aspects of content that are not necessarily misconceptions, but are acknowledged as posing difficulty in understanding. In this case, Khaya expresses an understanding that the "simultaneity" of reverse reactions in chemical equilibrium is an aspect that is difficult to understand. The next sentence re-emphasizes

Brief outline of how intentions of the lessons are covered	State the Le Châtelier's principle and ask learners to write down their own understanding of the definition. Apply it to the reactions that are at equilibrium using the changes in the temperature and concentration of reagents. Note: When discussing the addition of water and solids, particularly, use the Kc expression to predict the response of the equilibrium. Also use Le Châtelier's principle and the Kc expression interchangeably when determining the effects of disturbances on the equilibrium and not just one mechanism

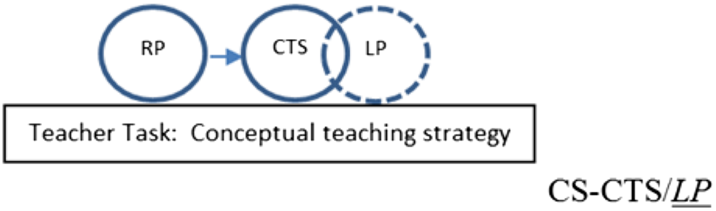


Fig. 4 Sipho's TSPCK episode displaying LP as an implicit component

another important element of chemical equilibrium, that is: "…important condition for the existence of an equilibrium system is that the change which occurs must be reversible" (CS). In this case, emphasis is placed on the understanding of reverse reactions per se, which is a concept that could have been taught previously, now brought into the explanation as a pre-concept important in understanding chemical equilibrium. This reference is also considered an element of CS. The closing sentence refers to the use of representations clarifying how the "reversibility" in reverse reactions is represented symbolically: "the reversibility of a change is represented by a double arrow" (RP). While Khaya's episode also contains three different components of TSPCK, these components interact in a complex manner, including drawing on one of the components more than once.

The last TSPCK episode of Khaya's richly displayed four components of TSPCK interacting, expressed in the sequence "CS/RP/WD/CS-RP/LP." As observed, there is an

Equilibrium can be established in a closed system, between liquid water and the water vapour when the evaporation occurs at the same rate as condensation. The Equilibrium is dynamic in nature because there is a state of balance as evaporation and condensation keep on taking place at the same rate. Important condition for the existence of an equilibrium system is that the change which occurs must be reversible. The reversibility of a change is represented by a double arrow

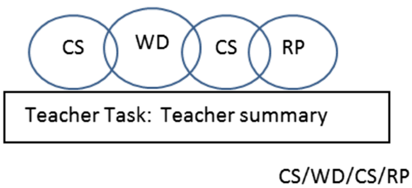


Fig. 5 A TSPCK episode with a repeating TSPCK component

additional level of sophistication in the permutation that was brought about by the presence of an extra fourth component as well as the existence of repeating components. In this case, it is the components of "Curricular Saliency" (CS) and "Representations" (RP) that are repeated, see Fig. 6.

The concept of the dynamic nature of chemical equilibrium is richly explained from multiple, but different considerations whose connections are explicitly indicated. Other examples of four-component TSPCK episodes with different permutations of sequences were also observed for pre-service teacher Hloni "CS/RPCS-WD/LP" and Themba "CS/WD/LP/RP," respectively.

The examples presented have been selected to carefully characterise how the interactions among the TSPCK components were observed to emerge in varied and complex permutations. The variation and complexity were seen to emerge in TSPCK episodes of the same PST, even from two individual PSTs targeting the same objective in the same topic as shown between Khaya and Sipho.

The New Understanding about TSPCK Component Interactions

The *first* new finding, about the nature of TSPCK component interactions, was that they largely occurred among three of the components. This is evident in Table 4, which presents the 30 TSPCK episodes re-organized by quantity of components in an episode.

The component of curricular saliency (CS) was uniquely observed to be most common across all but one TSPCK episode (<u>*LP*</u>/CTS/RP. It is also the most repeated within an episode. Some of the three-different component episodes had component(s) repeated making them slightly more sophisticated than their standard counterparts. The components of representations (RP), "Learner Prior Knowledge" (LP), and "What is difficult to understand" (WD) were next in frequency. The component of the conceptual teaching strategy component was found to be the least prominent. It was further observed that when this component was present in a TSPCK episode, then the component of LP was implicitly displayed as shown in the TSPCK sequences of Khaya and Sipho in Table 2.

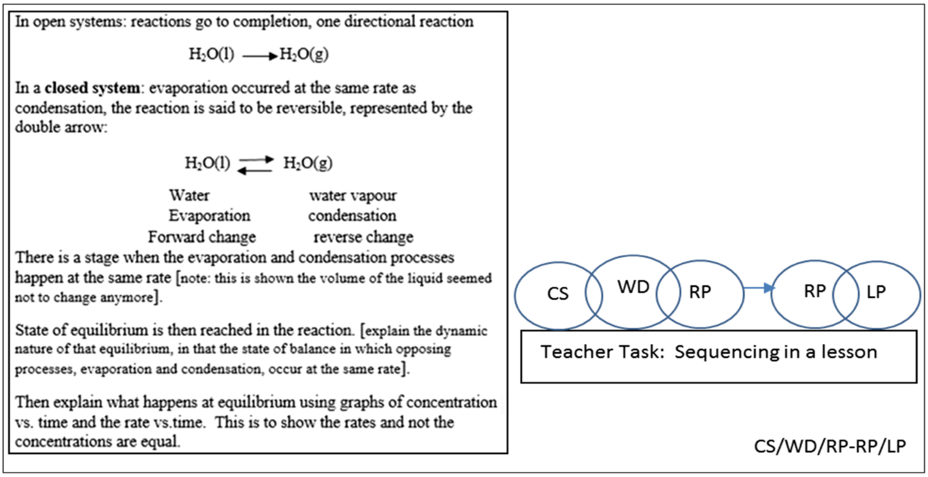


Fig. 6 Khaya's richer TSPCK Map

Table 4 The nature of component interactions and the corresponding teaching tasks

TSPCK episode	Quantity	TSPCK Sequence	Nature of teacher task
Three-component TSPCK episodes	17	*LP*/CTS/RP CS-RP/WD (9) RP-CS/LP (2) CS-LP/RP (2) RP/LP-CS CS-LP/RP CS-CTS/*LP*	Conceptual teaching strategy
Three-component TSPCK episodes with a repeating component (mostly CS)	8	CS/WD/CS/RP CS/CS/LP/RP CS/WD/RP-CS CS-WD-RP/CS (3) RP-CS/LP-RP CS/WD/LP/RP	Summary of most important content knowledge in a lesson
Four-component TSPCK episodes with a repeating component	5	CS/WD/RP-RP/LP (2) CS/RP/CS-WD/LP CS/WD/RP-CS/LP CS-RP/WD-CS/*LP*	Teaching sequence

The *second* new finding reveals the structural arrangement behind the TSPCK component interactions. It is observed, as shown by the TSPCK sequences in Tables 2 and 4, that the content-specific components of TSPCK interact in clearly distinguishable structural formats. The observed structure was either a completely interwoven format as shown, for example, in the TSPCK episodes of Khaya in Fig. 5; or a combination of linear and interwoven formats co-existing in a single TSPCK episode such as in Figs. 4, 6, 7, and 8. A TSPCK episode with a linear structural component interaction had clear connecting phrases that convincingly indicated a sequence where one aspect is first completed then the next is being discussed. Phrases used are shown as selectively boxed text in Figs. 7 and 8. These were words such as "...another thing …" as shown in Mimi's TSPCK episode in Fig. 7 or, "I will then…," shown in Nduna's TSPCK episode in Fig. 8.

Interwoven component interactions emerged as conceptual explanations mentioned in the same sentence (see underlined text in Figs. 7 and 8). In another case, they were identified by the repeat of the same concepts as starting points in the next sentence, illustrating connectivity, as in Fig. 5. The structural arrangement of a combination of linear and interwoven component interactions were found to be the most common arrangement in most TSPCK episodes.

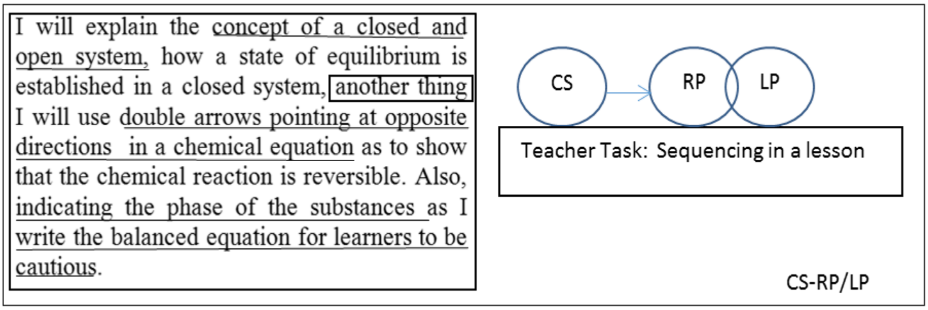


Fig. 7 Mimi's TSPCK episode and map

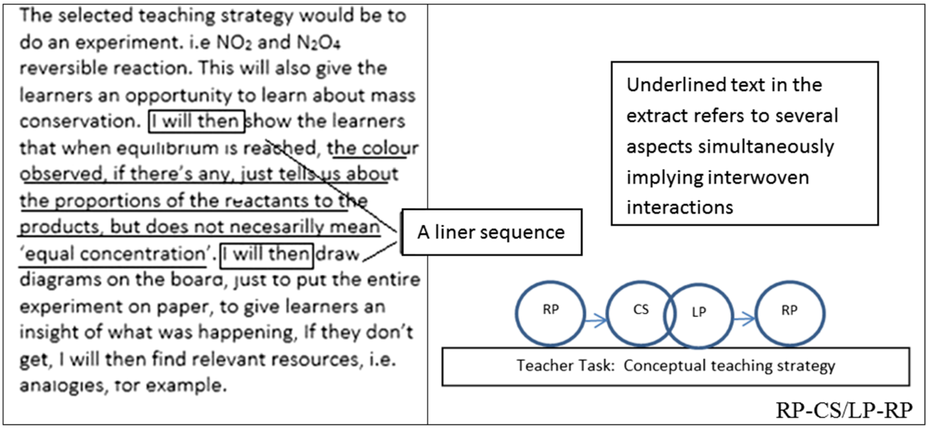


Fig. 8 Nduna's TSPCK episode and map

The *third* novel finding responded to the second research question about the nature of the teaching tasks from which TSPCK component interactions were observed. It was found that complex component interactions seem to emerge from specific kinds of teacher tasks. Three noticeable teacher tasks were identified as activities that promoted the emergence of TSPCK episodes: (a) recommendations for conceptual teaching strategies, (b) summary of the most important content knowledge in a lesson; and (c) sequencing of a lesson. The most sophisticated TSPCK episodes were seen to emerge from this last mentioned teacher task.

TSPCK Episodes from Recommendations of Conceptual Teaching Strategies

The summary table of TSPCK episodes (Table 4) reflects a pattern in which teacher tasks that required the formulation of conceptual teaching strategies facilitated mainly the emergence of three-component TSPCK episodes, which were more in abundance. These were tasks were PSTs spelled out their planned teaching actions as shown in Nduna's episode in Fig. 8 earlier.

TSPCK Episodes from Summary of the Most Important Content Knowledge

Teacher tasks requiring a summary of the most important content in a lesson facilitated the emergence of slightly different kind of three-component TSPCK episodes. These were three-component TSPCK episodes with a repeating component, which was mostly the component of CS. These episodes reflected a slightly increased level of sophistication compared to their simpler counterparts, as they reflected repeated emphasis on important concepts, and in so doing, they revealed different sides of a concept. The TSPCK episodes of Khaya in Fig. 5 and Ben in Fig. 9 illustrate this observation. Looking closely at Ben's episode, similar to that of Khaya in Fig. 5, the component CS is repeated twice reflecting different elements offered by the component.

The first component to emerge is that of CS seen by the reference to concepts that are core to establishing chemical equilibrium, that is, a *closed system*. The second aspect, while not part of the Big Idea is, however, a needed pre-concept to be understood as seen in the statement "reversible reactions that happen in a closed system eventually reaches an equilibrium". The

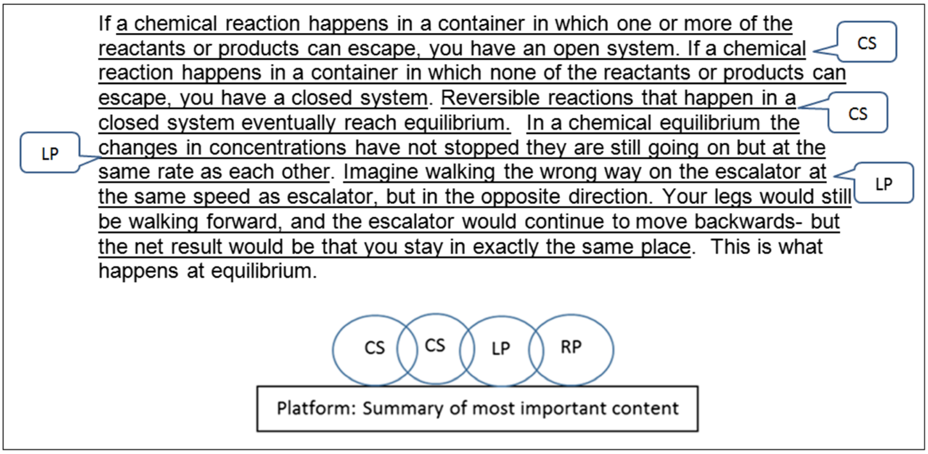


Fig. 9 Ben's TSPCK episode and map from summary of a lesson

unique feature emerging from responses triggered by teacher tasks on *summaries of the most important content knowledge* is the repetitive usage of the component of curricular saliency and the associated emphasis on its different aspects.

TSPCK Episodes from Sequencing a Lesson

According to the summary in Table 3, teacher tasks that require articulation of a sequence in which a lesson will unfold, emerged to reveal TSPCK component interactions with the most complexity. The observed increased sophistication could be linked to the highest quantity of different TSPCK components present, as well as the existence of a complex component structure where both interwoven and linear structures are co-existing. Examples are the TSPCK Sequence CS/RP/WD/CS-RP/LP seen in the TSPCK episodes of Khaya (Fig. 6) and that of Hloni "CS/RP/CS-WD/LP," in Fig. 10.

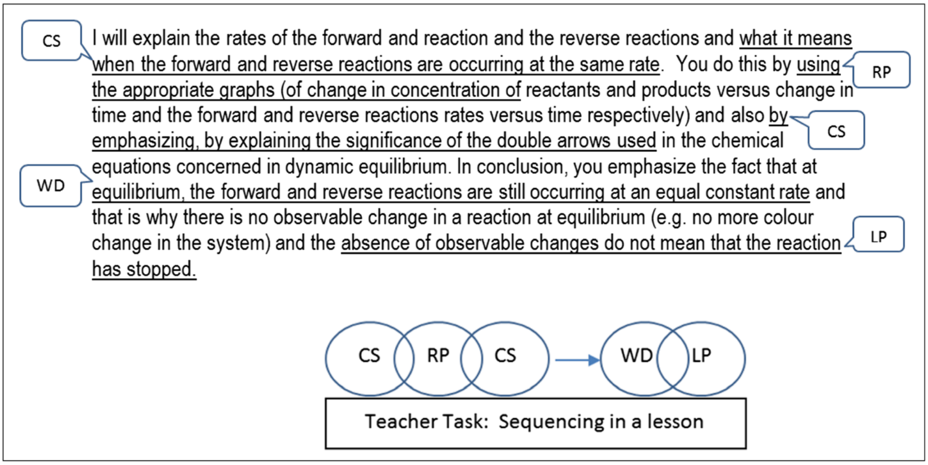


Fig. 10 A richer four-component TSPCK episode from sequencing a lesson (Hloni)

It is observed that the teacher's task of sequencing events in this lesson facilitated the thinking that brought out more multiple component interactions than any other teacher's task in this study.

Discussion and Conclusion

The purpose of this study was to illuminate the structural arrangement in which the content-specific components of the TSPCK construct interact among each other and the nature of the tasks from which such arrangements emerge. The rationale was argued in relation to the multidimensional nature of PCK, which is characterised in the refined consensus model (RCM) of PCK generated from the PCK Summit II. It was pointed out that this demanded an understanding of the nature of each grainsize version of PCK. The importance of establishing such understanding was further argued as a moral need to teach PCK to PSTs with clarity of the version of PCK targeted and with explicit emphasis of the features that lead to the development of a sophisticated level of the construct.

PCK and Its Implementation in Science Education

The first finding as presented in Tables 2, 3 and 4 indicated that PSTs generated TSPCK episodes with component interactions that are varied in combinations and peculiar to each participant. This observation was not surprising as a similar observation with the broader, discipline version of PCK, the science discipline PCK based on models such as Magnusson's et al. (1999), has been reported in the literature (Aydin et al. 2014; Park and Chen 2012). However, the finding remains important as it talks specifically to TSPCK, one of the grainsize in the continuum of PCK reflected in the RCM of PCK. The finding gives clarity in more the ways in which the construct of TSPCK is similar to the discipline PCK, while retaining its epistemological difference of being localized in a topic. According to this finding and previous reports (Aydin et al. 2014; Park and Chen 2012), that discipline PCK and TSPCK share a similar attribute, in that they both emerge from component interactions, which are complex and idiosyncratic in nature. The idiosyncratic nature of component interactions is seen to bring to life the idea of personal PCK (pPCK) at the grainsize of topic-specific level. Based on the findings, it is reasonable to attribute the observed idiosyncratic nature in the TSPCK sequences to personal TSPCK. This is supported by the PSTs working with all the components of TSPCK, thus legitimizing their outputs as reflecting TSPCK from the perspective of their personal realm. One could then compare their individually generated responses in the CoRes to an exemplary CoRes on chemical equilibrium generated and agreed to by a larger community to reflect the shared best practice in teaching topic. Such a CoRes on chemical equilibrium, if it exists, would then be regarded as reflecting collective TSPCK in the topic. In such a scenario, the observed idiosyncratic nature of component interactions emerges as a feature that distinguishes TSPCK across the collective-personal realms of PCK. This findings adds credibility to the idea of the multidimensional nature of PCK.

With respect to new findings, the first finding on the structure of TSPCK component interactions revealed the complex nature of the component interactions to be influenced by two factors, namely, the quantity of different components and their structural arrangement.

TSPCK episodes found to have a higher number of different components, and/or with one component repeated more than once, emerged from qualitative extracts that displayed *more depth* in understanding. Examples of these were found in PSTs Khaya in Fig. 6 and Hloni in Fig. 10 displaying exemplary four-different component TSPCK episodes with one component repeated more than once. These brought in additional depth as the concept was explained from the different perspectives. Looking at how the concept of "reversible reactions" was particularly unpacked by Khaya (Fig. 5) in an explanation on dynamic chemical equilibrium another example that illustrates the point. Khaya brought the concept firstly as a needed *pre-concept*, then highlighted the *difficulty* learners have in understanding the aspect of simultaneity found in reverse reactions when in chemical equilibrium and lastly explained how this aspect (reversibility) is *represented* symbolically. This demonstrated, in addition to conceptual understanding, the consideration of different teacher knowledge about teaching reversible reactions. So, the value derived from the presence of multiple components of TSPCK in a planning segment is the visualization of what Geddis and Wood (1997 p. 612) called the transformation of content knowledge through a "variety of different kinds of knowledge."

The second new finding revealed the distinguishable structural nature of TSPCK component interactions. The components of TSPCK were found to interact among one another in distinguishable, completely interwoven arrangements, in some cases in a combination of a linear and interwoven structural arrangement co-existing in a TSPCK episode. Completely interwoven structural arrangements appeared to display the *connections* between concepts more explicitly as seen in the TSPCK Maps of Khaya in Fig. 5 and Ben in Fig. 9. They were prevalent in episodes with multiple components present. This structural arrangement was brought in by the visible effort to continue an explanation of a concept from one sentence connecting into the next. Examples of these are seen in the extracts of Ben and Hloni in Figs. 9 and 10, respectively. These visual connections of concepts across the sentences ushered in coherency and revealed the connections between concepts more explicitly. Such desirable effort turned the explanation of dynamic chemical equilibrium into a non-threatening and accessible story. This finding revealed the features to be developed when aspiring for constructing conceptual topic explanations with depth. These are consideration of multiple components of TSPCK, where the connections from one to another are explicit. This finding is in line with the statement by Park and Chen (2012 p. 937) that "the topic-specificity depends not only on the components constitute of a teacher's PCK for a particular topic, but also on how and to what degree those components interact with one another."

It is also important to note that TSPCK component interactions that exhibited sophistication by virtue of having both multiple components of TSPCK and the interwoven component structure feature emerged mostly from teacher tasks eliciting the reasoning about the sequencing of a lesson and those requiring efforts to summarize the most important content knowledge of the lesson. This suggests that the use of these tasks in PCK-based teacher preparation programs would promote the emergence of sophisticated transformation of content knowledge.

In conclusion, while the study had limitations in a sense that the findings were drawn from the efforts of PSTs (rather than practicing teachers), also from a planning rather than classroom enactment, they remain important as they shed light on several aspects related to the renewed narrative on the multidimensional nature of PCK. At a conceptual level, the findings assisted in bringing some clarity on features that bring about the desired sophistication in the quality of

TSPCK. Furthermore, they added insight into the ways TSPCK is similar but different from discipline PCK. They also illustrated the possible ways in which TSPCK plays out in the collective-personal realms of PCK. From a methodological perspective, the findings offer teacher education program a suggestion of teacher tasks and the criteria behind sophisticated TSPCK that may be infused in the elementary steps of learning to acquire TSPCK.

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