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Connections between content knowledge and personal pedagogical content knowledge in electricity topics

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Abstract: This study examines primary school pre-service teachers' content knowledge, personal pedagogical content knowledge (pPCK), and connections between pre-service teachers' content knowledge and pPCK in serial and parallel connection in the electricity topic. Magnusson model, PCK mapping approach, and Refined Consensus Model were used as a theoretical framework. A total of 26 primary school juniors participated in the study. Convenient sampling was used to collect data, which was gathered through two open-ended questions. Data analysis included inductive coding for content knowledge, and the PCK mapping approach was used to analyze participants' pPCK. Then, the two analysis results were compared to see the connections between content knowledge and pPCK. The findings revealed three different knowledge areas, namely personal PCK, general pedagogical knowledge, and pseudo-PCK. Comparison of content knowledge and PCK results revealed that those who knew the content could produce personal PCK that aligns with high-quality teaching. On the other hand, the ones having limited content knowledge produced either general pedagogical knowledge that ignores content knowledge or pseudo-PCK using wrong content knowledge in their teaching plan. These results can help us to understand the complex relationship between content knowledge and PCK.

Keywords: Content Knowledge, Electricity, Personal Pedagogical Content Knowledge

Elektrik Konusunda İçerik Bilgisi ile Kişisel Pedagojik Alan Bilgisi arasındaki Bağlantılar

Öz: Bu çalışma sınıf öğretmenliği öğretmen adaylarının elektrik konusundaki seri ve paralel bağlama hakkındaki içerik bilgisini, kişisel pedagojik alan bilgisini (kPAB) ve öğretmen adaylarının bu iki bilgi türü arasındaki bağlantılarını araştırmaktadır. Araştırmada Magnusson modeli, PAB haritalama yaklaşımı ve Geliştirilmiş Uzlaşı model kavramsal çerçeve olarak kullanılmıştır. Çalışmaya bir özel üniversitede öğretim gören 26 sınıf öğretmenliği 3. sınıf öğrencisi katılmıştır. Çalışmada kolay ulaşılabilir örnekleme yöntemi seçilmiş ve veriler iki açık uçlu soru ile toplanmıştır. İçerik bilgisi analizinde tümevarımsal kodlama, kPAB analizinde PAB haritalama yaklaşımı kullanılmıştır. Bu iki analiz sonucunun karşılaştırılmasıyla içerik bilgisi ve kPAB arasındaki bağlantılar ortaya konmuştur. Sonuçlar 3 farklı bilgi alanını ortaya koymaktadır. Bu bilgi alanları; kişisel PAB, genel pedagoji bilgisi ve sahte PAB'dır. İçerik bilgisi ve PAB analizlerinin karşılaştırılması sonucunda, sadece konuyu bilen öğretmen adaylarının kaliteli öğretimle ilişkilendirilen kişisel PAB'ı ders planlarına yansıttıkları görülmüştür. Öte yandan konuyla ilgili sınırlı bilgisi olan adaylar ders planlarında içerik bilgisini ihmal eden genel pedagoji bilgisini veya yanlış içerik bilgisinin öğretimine odaklanan sahte-PAB'ı kullanmışlardır. Bu sonuçlar PAB ve içerik alan bilgisi arasındaki karmaşık ilişkinin anlaşılmasına yardımcı olabilir.

Anahtar Sözcükler: İçerik Bilgisi, Elektrik, Kişisel Pedagojik Alan Bilgisi

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Effective instruction is essential for students' learning. Some characteristics of effective instruction are teachers' pedagogical content knowledge (PCK), classroom climate, classroom management, teacher beliefs, teacher professional development, and teacher collaboration with colleagues (Coe et al., 2014). As effective instruction is a complex structure, and it is difficult to study the abovementioned aspects of effective instruction together, this study focuses on only PCK in terms of effective instruction.

According to Shulman (1986), content knowledge (CK) is important, but it is not enough for successful teaching. At this point, PCK gains importance. PCK is the transformation of content knowledge in a way that students can understand the content. When teachers transform content knowledge, they address students' needs and use specific instructional strategies like powerful analogies and illustrations to support students' understandings (Shulman, 1986). This knowledge is important because PCK shows to what extent a teacher is capable of teaching (Magnusson et al., 1999).

PCK is the transformation of other knowledge types, like content knowledge, and the aim is to make content knowledge understandable for students. Therefore, content knowledge can be thought of as raw knowledge, and PCK can be thought of as processed knowledge. So, solving the puzzle regarding the link between content knowledge and PCK seems to be one of the ultimate goals in PCK research to understand the nature of PCK. In line with this, Lederman and Gess-Newsome (1992) reported that if the relation between content knowledge and PCK is understood, PCK and its implications for the class can be better known. However, the transformation of content knowledge into PCK is not an automatic process because teaching is complex (Bartos et al., 2014). This situation makes studying content knowledge and PCK difficult.

One, and maybe the most important factor, blurring the relationship between content knowledge and PCK is the learning context. Accordingly, the learning context, including policies, standards, class dynamics, and individual student attributes, affects PCK as this learning context acts as a filter or amplifier for PCK in the class. In other words, learning context can limit or support PCK depending on the learning environment (Carlson & Daehler, 2019). As learning context affects actual PCK positively and negatively, it is difficult to observe the link between content knowledge and PCK when there is a learning context and its effect on PCK. To better observe the connections between content knowledge and PCK, therefore, the learning context was removed from the study to avoid its potential impacts on pPCK. In this way, we believe the connections between content knowledge and PCK become clearer. To sum up, this study aims to make contributions to our understanding of the connections between PCK and content knowledge.

Within the scope of this study, after PCK, the second important topic is content knowledge, as the study seeks connections between content knowledge and PCK. Content knowledge is one of the professional knowledge bases that teachers are expected to have to become experts. Content knowledge refers academic content of a discipline, and this knowledge can be general knowledge about that discipline or knowledge related to specific topics (Carlson & Daehler, 2019).

PCK is a topic-specific construct because each topic has its teaching style, method, and approach (Veal & MaKinster, 1999). The electricity topic was selected in this study as the specific topic because of the following reasons: first, electricity is an abstract topic, and students can not understand it easily (Sencar et al., 2001). Second, the students have many misconceptions about electricity (Özmen, 2024). Third, students have practical difficulties with electricity, such as setting electrical circuits (Ayvacı et al., 2023; Özmen, 2024). Results of the current study may inform us regarding how a difficult electricity topic is taught and what could be done to improve the quality of teaching electricity.

Theoretical Framework

Researchers proposed and used different models to address teachers' PCK. Some of these models are the Magnusson model (Magnusson et al., 1999), the PCK mapping (Park & Chen, 2012), the Consensus model (CM) (Gess-Newsome, 2015), and the Refined consensus model (RCM) (Carlson & Daehler, 2019). The current study is framed on the Magnusson model, PCK mapping, and RCM. Therefore, definitions and claims of these models represent what we understand from PCK. Firstly, this study was constructed on Magnusson model that includes 5 different components which are orientation of teaching science (OTS) (i.e., general views toward science teaching), knowledge of science curriculum (KOC) (i.e., goals, objectives, specific curricular programs, knowledge of materials, connecting objectives of same years and different years topics), knowledge of students' understandings of science (knowledge of learner-KOL) (i.e., requirements for learning, students' difficulties and misconceptions), knowledge of assessment in science (KOA) (i.e., what to assess and how to assess students' learning), and knowledge of instructional strategies (KOIS) (i.e., subject-specific strategies and topic-specific strategies including activities and representations) (Magnusson et al., 1999). As PCK is a topic-specific construct, and content is central to the PCK; therefore, OTS that is related to broader goals instead of specific science content was removed from the current study, and the other 4 components were used similarly to previous research (Bravo & Cofre, 2016). Similarly, Henze and van Driel (2015) reported that PCK has 4 dimensions, which are KOIS, KOC, KOA, and KOL, and OTS is not a PCK component, but it shapes PCK. Regarding the use of these 4 components, Barendsen & Henze (2019) reported that these 4 components are universal, pedagogically simple, entire, consistent with education materials, and exist in other pedagogical models. Therefore, it is useful to use these 4 components to understand PCK.

Although the Magnusson model is useful to understand PCK and has been used several times in previous research, it has one main limitation that the model ignores the interaction between the 4 components and only considers the individual components. Therefore, Park and Chen's (2012) PCK mapping approach was added to the current study to support its theoretical aspect. According to Park and Chen (2012), a strong PCK should include interaction among PCK components. The more interaction between PCK components, the stronger the PCK the teacher has. In other words, the interaction between PCK components gives information about the quality of PCK. Chan (2022) also added that the PCK mapping approach identifies, visualizes, and quantifies the integration among PCK components, and we can understand the teachers' PCK in this way.

The third and main model used in this study is the refined consensus model (RCM). Before RCM, researchers proposed the Consensus Model at the first PCK summit. The consensus model distinguished personal knowledge (PCK) and public knowledge (i.e., teacher professional knowledge bases and topic-specific professional knowledge). This model was also the first model that proposed PCK is both a knowledge that the teacher has and a dynamic knowledge related to teacher practice (Gess-Newsome, 2015). However, the details of the PCK were absent in the consensus model; therefore, PCK researchers met at the second PCK summit. In the 2nd summit, researchers proposed the Refined Consensus Model (RCM) built on the consensus model (Carlson & Daehler, 2019). This model (i.e., RCM) was used as the third model for this study because RCM explains the complex structure of teaching and focuses on collaboration among teachers, teaching, planning, and reflection cycle of an individual teacher, and teacher experience (Carpendale & Hume, 2019). RCM identifies three different realms of PCK, namely collective PCK (cPCK), personal PCK (pPCK), and enacted PCK (ePCK). Collective PCK is public and generalizable, and this knowledge is formed through research and cooperation between teachers. On the other hand, personal PCK is the sum of an individual teacher's knowledge and skills improved as a result of the teacher's experience, interaction with students, and cooperation with colleagues. Next, enacted PCK is the knowledge and skills used in actual teaching. Enacted PCK depends on the context and teaching moment, and it varies depending on students' needs in that moment (Carlson & Daehler, 2019). These three realms of PCK continuously affect each other, and there is a feedback loop among them that improves the PCK (Carlson & Daehler, 2019). Among these three PCK realms, what actually improves is pPCK, which is the reservoir of knowledge (Carlson & Daehler, 2019). Therefore, this study specifically focused on pPCK, so the scope of this study does not include cPCK and ePCK. In line with this, Irmer et al. (2023) reported that pPCK should be researched because pPCK research shows how teachers gain and adjust their PCK.

Specifically, pPCK is individualized knowledge and skills that a teacher brings to class. This knowledge is topic-specific. pPCK is more stable than ePCK but can be identified more easily. This knowledge reflects our overall understanding and insights about a topic as a teacher, and this knowledge is used for planning and future teaching. After pPCK is used as reservoir knowledge in the teacher's plan, the teacher activates ePCK, integrating pPCK with specific students' needs. Through the plan, teach, and reflect cycle, ePCK is used and improved. Improvements of ePCK, then becomes a part of pPCK, leading to improvement for pPCK (Alonzo et al., 2019).

To sum up, this study includes a comprehensive framework including three different PCK models, which are the Magnusson Model, the PCK mapping approach, and the refined consensus model. Each of these models is distinct and complementary. Therefore, studying these three models together facilitates our understanding of PCK. Accordingly, the Magnusson model was selected as it includes important aspects of teaching like instructional strategy and curricular objectives. The PCK mapping approach was selected as the Magnusson model ignores the interactions between PCK components. In other words, the PCK mapping approach compensates for the weakness of the Magnusson model regarding the interaction between PCK components. But still, these two models do not provide sufficient information regarding which realm of PCK is considered. For example, these two models can be used for both teachers' knowledge in action and knowledge on action. These nuances are important in PCK because knowledge in action refers to teachers' actual teaching and their reasoning in this process (i.e., ePCK). On the other hand, knowledge on action refers to teachers' plans and reflections about their teaching (i.e., pPCK). In order to clarify which specific PCK realm was considered, the refined consensus model was added to the other two PCK models as part of the theoretical framework. By adding the refined consensus model, the current study could enlighten participants' pPCK.

Literature Review

The study considers the connections between content knowledge and pPCK in the electricity topic. Therefore, the literature review includes the previous research seeking the relations between content knowledge and PCK. The current study was conducted with primary school pre-service teachers. As pPCK changes with experience (Carlson & Daehler, 2019), the connection between content knowledge and PCK might also change depending on the participants' experience level (i.e., pre-service teachers and in-service teachers). Therefore, the literature review includes only the studies that connect PCK and content knowledge at the pre-service level. The studies held with in-service teachers were excluded from the literature review.

Theoretically, content knowledge is a prerequisite for strong PCK, as content is central to PCK. In line with this, many studies held with PST supported the idea that content knowledge and PCK are positively related (Aydın et al., 2010; Aydın & Boz, 2012; Boz & Boz, 2008; Canbazoğlu et al., 2010; Kaya, 2009; Özden, 2008; Schiering et al., 2023; Uşak et al., 2011). However, the relation between content knowledge and PCK reported in previous research seems to be descriptive and superficial because the previous research can not explain why such a positive relation between PCK and content knowledge exists. One study by Sickel and Friedrichsen (2018) might help explain the possible reasons for the positive link between content knowledge and PCK. In this study, Sickel and Friedrichsen (2018) studied beginning biology teachers in natural selection topics and used core ideas, which are the important points of that content, in their PCK study. Researchers reported that these core ideas act as a bridge that connects content knowledge and PCK. Accordingly, researchers reported that the ones who got the evolution course, in other words, who knew the content well, could use core ideas in the interactions among the PCK components. On the other hand, the ones who did not know the content well did not use such core ideas in their PCK maps. Such an analysis shows clear connections between the same teacher's content knowledge and PCK, and seems to be an insightful approach to solving the problem regarding how and why content knowledge and PCK are positively related with each other.

Although research mainly reported a positive relation between content knowledge and PCK, some of the research reported partial support for the positive relation between content knowledge and PCK (Kapyla et al., 2009). Even worse, some studies reported no connection (Uşak, 2009) or a negative relation between content knowledge and PCK (de Jong & van Driel, 2004; Kind, 2009; Mapulanga et al., 2024).

To sum up, previous research focused on the relationship between content knowledge and PCK to better understand PCK, and most of the studies found positive relationships between the two constructs; however, they did not adequately explain why there is a positive relationship between the two constructs. Sickel and Friedrichsen's (2018) study, which emphasizes core ideas in that content, seems to be insightful regarding the explanation of the relation between content knowledge and PCK. Still, being cautious of a pre-determined positive relation between content knowledge and PCK seems to be plausible, as some of the previous research showed either no link between content knowledge and PCK or negative relations among them.

All in all, the literature review shows there is a lack of explanation regarding why there is a positive link between PCK and content knowledge, if any, and the use of core ideas can be informative to understand the nature of the positive link between the two constructs.

Significance of the study

The study has three main significances. First, core idea is a bridge between content knowledge and PCK; however, previous PCK research mainly did not focus on core ideas (Sickel, 2012), therefore although there have been many research conducted on the relationship between content knowledge and PCK, very little knowledge has been gained regarding why and how content knowledge and PCK are related if these two constructs are positively related as most of the previous research proposed. The fewer core idea is used, the more precision we get regarding the connection between content knowledge and PCK, because if we use only one core idea, the PCK will be shaped on this idea, and we can easily establish a connection between content knowledge (i.e., core idea) and the exhibited PCK. On the other hand, if we use several core ideas in a unit as part of content knowledge, the teacher will still exhibit a PCK, but it is difficult to see which core idea is connected to the exhibited PCK. Such a situation may decrease the precision of the connection between content knowledge and PCK. Therefore, we used only one core idea in the electricity topic, and the core idea was the comparison of bulb brightness between serial and parallel circuits. By using this core idea, the study can add some explanations about the connection between content knowledge and PCK, which might increase our understanding of PCK.

The second significance of the study is about the participants. In their review study, Chan and Hume (2019) reported that PCK research has been mainly conducted with secondary-level teachers. Most probably, researchers chose secondary level teachers as PCK is based on content knowledge, and content knowledge emphasis increases in higher grade levels, like secondary schools. However, the primary school level is also important, and science is learnt at this level at first. Therefore, primary school teachers' PCK should also be investigated, and their strengths, weaknesses, and needs should be revealed to improve the quality of science teaching. To contribute to the closing of this gap regarding the lack of PCK studies at the primary school level, this study selected primary school pre-service teachers as participants.

The last significance is related to the phases of the PCK. Chan and Hume (2019) claimed PCK is comprised of three phases, which are the pre-active phase, the interactive phase, and the post-active phase. However, previous PCK research did not report these phases, and reported their results as if PCK had only one phase, ignoring specific PCK phases. Chan and Hume (2019) call on researchers to study different phases of PCK. If we study and understand different phases of the PCK, we can better understand the PCK. For example, if a teacher prepares a lesson plan for teaching, this plan specifically informs the pre-active phase of PCK. Similarly, by focusing on teachers' plans that reveal their pPCK, findings of this study can add specific information to the literature about the pre-active phase of the PCK.

To sum up, this study has three main questions:

1. What is the primary school pre-service teachers' content knowledge in serial and parallel circuits?
2. What is the primary school pre-service teachers' personal pedagogical content knowledge (pPCK) in serial and parallel circuits?
3. What are the possible connections between content knowledge and personal pedagogical content knowledge when primary school pre-service teachers reveal their content knowledge and personal pedagogical content knowledge in serial and parallel circuits?

Method

Research Design

Qualitative research design was used in this study, and an example of qualitative research, basic qualitative research, was used. In basic qualitative research, participants construct their world, and researchers try to understand the meaning of those constructions (Merriam, 2009). In this study, participants constructed their understanding of parallel and series circuits through their drawings and written explanations, and they constructed their personal PCK by planning their teaching about parallel and series circuits. By interpreting their drawings, explanations, and plans, we derived meanings about their content knowledge and pPCK in this basic qualitative research.

Context

The study was carried out in one of the private universities located in Ankara, Türkiye. Education language of the university is English. The study was held in the primary education department. After one year of English language preparation, the students (primary school PSTs) start their four-year-long primary school teaching education. The students get common courses with other faculty students, general education courses like educational psychology, and specific courses about their department, like science, math, and social science. Science courses that primary school PSTs take are fundamental science in primary school that focuses on science content knowledge, laboratory applications in science, emphasizing application of scientific endeavor, and a science method course dealing with the teaching aspects of science. The students who enrolled in the primary education program got mainly social science and math courses in their high school. Therefore, students' science content knowledge did not improve so much when they started their university career.

Participants

In the primary education department, PSTs in the third year of their four-year-long program complete science courses. Therefore, PSTs in their third year were selected for the study, and the students in the first and second years were excluded from the study. Likewise, PSTs in the last year of their program were not included in the study as they focused on their career, so they might not focus on the study and might give limited information about their content knowledge and pPCK. In total, 26 primary school PSTs in their third year participated in the study. Two of the participants were male, and the rest of them were female. Convenient sampling was used for participant selection, and the third-grade-level PSTs who were available were invited to the study, and the volunteer ones participated in the study. In this study, participants were selected from the private university the researcher works through convenient sampling in order to save time, cost, and energy. Therefore, PSTs from public universities were not included in this study. In line with this, the research findings represent only the situation in this private university, not the public universities.

Ethics

Before the study was conducted, ethical permissions were obtained from the university’s Human Research Ethics Committee (Ethical Committee decision number: 2025-48/08). Participants were informed they could withdraw from the study whenever they wanted without any excuse. No incentive or punishment was provided to participants in response to their participation in the study. They were just informed that their data would be used for scientific research. Pseudonyms were given to participants to protect anonymity. Accordingly, participants were sorted from ID1 to ID26. In this way, each participant was labelled. Participants’ data was also not shared with other people. Only anonymous papers were seen by researchers for inter-rater agreement. Lastly, no one got physically or psychologically harmed in the study.

Data Collection

Data was collected in the spring semester of 2024-2025, and lasted approximately two hours. Two open-ended questions were asked participants. In the first question, participants were asked to draw one basic electric circuit having bulbs connected in series, and one circuit having bulbs connected in parallel, and they were asked to explain which circuit’s bulbs shine brighter and why. For example, if participants use the same number of bulbs (e.g., 2 bulbs) for two circuits (series vs. parallel), the bulbs in the parallel circuit will shine more as the equivalent resistance is less in this circuit. Using the first question, participants' content knowledge was assessed.

In the second question, we aimed to reveal participants' pPCK. Performance in teaching tasks is one way to measure participants' PCK. According to this approach, the teacher writes a lesson plan, and this lesson plan informs what, how, and why the teacher does in teaching (Chan & Hume, 2019). Likewise, when teachers use lesson plans, the teachers exhibit their teaching scripts stored in their minds representing pPCK (Stender et al., 2017). Therefore, in the second question, we asked participants to prepare a lesson plan for teaching the same core idea mentioned in the first question (i.e., comparison of bulb brightness in series and parallel circuits). Specifically, we did not give any structure or direction in lesson plan preparation, and participants were free to form their own plans. We thought they could easily demonstrate their pPCK when there was no lesson plan format because any format might cause extra cognitive load for their thinking and decrease their performance in teaching task (i.e., lesson plan).

Data Analysis

Participants' content knowledge was assessed using their answer to the first question by considering their drawings and explaining the bulb brightness in different circuits (series vs. parallel). Inductive coding was used to analyze content knowledge. In this coding, the participant's drawing and explanation were compared with the scientific explanation, and the participant's content knowledge was coded based on to which extent participant's content knowledge matched with scientific explanation. The same procedure was repeated for all participants' content knowledge. After all participants' content knowledge was coded, the percentage and frequency of each code were calculated to understand the content knowledge of whole participants that addressed the first research question.

To answer the second research question, participants were asked to make a plan for teaching the same content (comparison of bulb brightness in series and parallel circuits), and these plans were analyzed to understand their pPCK. The PCK mapping approach was used for this analysis because the PCK mapping approach identifies, visualizes, and quantifies the integration of PCK components, and we can understand teachers' PCK in this way (Chan, 2022). In general, the PCK mapping approach is advised to use to reveal participants' ePCK. According to Park and Suh (2019), the teacher performs instruction, and this performance is video-recorded. Then, the teacher is invited to a video recall interview, and some questions about the teacher's teaching are asked. Then, the teacher's answers to questions prepared based on the video recordings are analyzed. In this analysis part, first, teaching segments are identified; these teaching segments are PCK episodes. Such segments also represent ePCK. Then, interactions between PCK components are identified (e.g., KOL-KOIS). The first part of the analysis is known as the in-depth analysis of explicit PCK. The second step of the analysis is the enumerative approach, in which the interactions among PCK components are visualized and quantified. In the last step of the analysis, constant comparative analysis, common patterns and themes are proposed considering the interactions among PCK components (Park & Suh, 2019).

We did not strictly follow this approach because this approach aimed to reveal ePCK. On the other hand, we focused on the pPCK in this study; therefore, our analysis for the pPCK was inspired by the PCK mapping approach explained by Park and Suh (2019). Accordingly, we read the participants' plan for teaching the core idea one by one. Then, we detected possible PCK components in these plans, and interactions among them similar to the in-depth analysis of explicit PCK (first step of PCK mapping approach). Then, we visualized and quantified each teacher's teaching plans using the enumerative approach, and we revealed the PCK profile for each teacher (second step of the PCK mapping approach). Then we compared different teachers' PCK profiles and teaching plans using the constant comparative method (third step of the PCK mapping approach). In this way, we could reach participants' pPCK, which is the answer to the second research question.

The main research question of the study was the last research question seeking an answer for the possible connections between content knowledge and pPCK. To find an answer to this question, we mainly focused on and compared participants' content knowledge results and their use of the core idea (comparison of bulb brightness in series and parallel circuits) in their teaching plans. When performing this analysis, we first noticed participants' content knowledge level. Second, we examined the same participant's teaching plan (i.e., pPCK), considering the use of the core idea in terms of accuracy and availability. For example, we looked for whether the participant used the core idea in the teaching plan (i.e., pPCK). If the participant used the core idea, then we looked to see whether the participant used the core idea accurately. Third, we looked for any connections by comparing the same participants' content knowledge and the use of the core idea in the plan (i.e., pPCK). For example, we examined whether participants transferred their correct knowledge to their teaching plan (i.e., pPCK), or we looked for what participants did in their plans (i.e., pPCK), if they did not know the content. This analysis was repeated for all 26 participants. Then, the results of the 26 participants in terms of the connections between content knowledge and the use of core idea exhibited in their teaching plan (i.e., pPCK) were constantly compared. Some patterns emerged as a result of this constant comparison analysis, and these patterns are the answer to the third research question, which sought connections between content knowledge and pPCK.

Validity and Reliability

Trustworthiness refers to validity and reliability in the qualitative research. Credibility, dependability, and transferability of the study support trustworthiness (Merriam, 2009). The study's credibility (i.e., internal validity) was supported by the use of multiple investigators and multiple theories. Accordingly, two researchers in science education contributed to the development of the data collection tool and analysis of the pPCK data. Likewise, one researcher from physics education checked the electricity content knowledge results. Similarly, an expert in PCK research provided feedback about the results in the connection between content knowledge and pPCK. Similar to multiple investigators, the use of multiple theories supported the credibility of the study. Accordingly, three main PCK theories were used in the planning, conducting, and analysis parts of the study. These theories were the Magnusson model, the PCK mapping approach, and the Refined Consensus Model (RCM). When the study was carried out, all aspects of these theories (i.e., the use of multiple theories) were considered, which supported the credibility of the study.

Dependability is about the reliability of the study (Merriam, 2009), and the dependability of the study was supported by inter-rater agreement. Accordingly, two science education researchers experienced in the electricity topic and PCK research analyzed the content knowledge and pPCK data separately. Inter-rater agreement was 90 % for the content knowledge, 85 % for the PCK analysis, and 90 % for the connections between content knowledge and pPCK. Researchers met after the analysis and reached a consensus on the disagreements.

Transferability, which refers to external validity in qualitative research, also supports the trustworthiness (Merriam, 2009). The findings of the study can be used in similar contexts. Accordingly, the researchers working in private universities with primary school PSTs can benefit from the findings. Other researchers and pre-service teachers can also benefit from the study if they deal with electricity content knowledge, the teaching aspect of content knowledge, and the connections between content knowledge and its teachability.

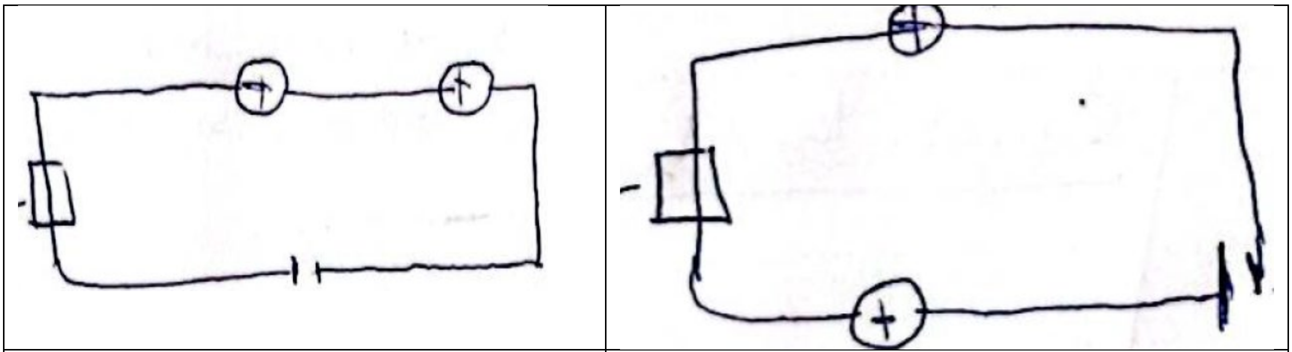
Results

Findings for content knowledge

Analysis of content knowledge revealed four hierarchical categories from a completely wrong answer to a scientifically correct answer. These four categories are explained below from the lowest level to the highest level in terms of content knowledge:

Category 1: Completely Wrong Drawing, Explanation, And Answer (The Lowest Level)

Nine of the participants' answers to the content knowledge question were in this category (35 %). These participants were ID11, ID12, ID13, ID15, ID17, ID19, ID20, ID21, and ID25. One of the completely wrong drawings, explanations, and answers is presented below in Figure 1 and the corresponding excerpt:



circuit in series	circuit in parallel

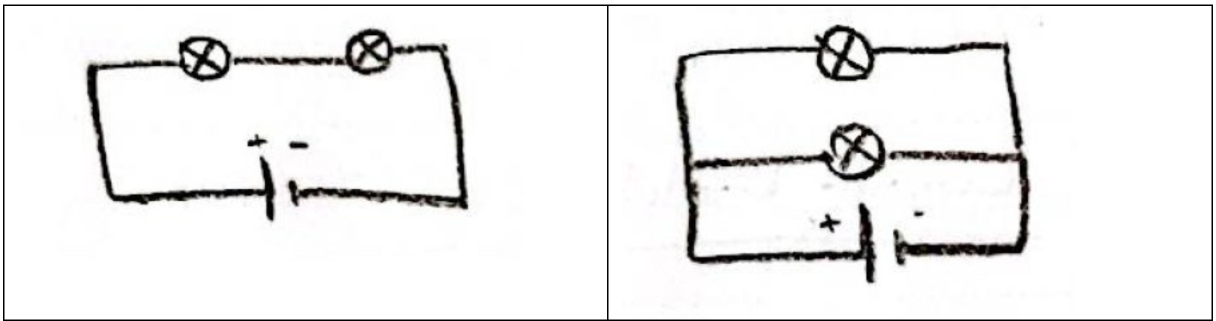
Figure 1. Drawing of ID15

ID15's explanation: Bulbs in parallel-connected circuits shine more because the same current passes through. However, the current is not the same in series.

As it is seen from Figure 1, ID15 could not draw a parallel-connected circuit because the drawn circuit is an example of a series-connected circuit. In line with this faulty drawing, ID15's explanations included a wrong answer, such as bulbs in series-connected circuits do not get the same current. To sum up, ID15's neither drawings nor explanations were scientifically correct for comparing the bulb brightness between parallel and series circuits.

Category 2: Correct Drawing, But Wrong Explanation and Answer (The Low Level)

Similarly, 9 of the participants, who were ID2, ID6, ID7, ID10, ID14, ID16, ID23, ID24 and ID26, were in this category (35 %). Figure 2 and the corresponding explanation show a specific example of this category.



circuit in series	circuit in parallel

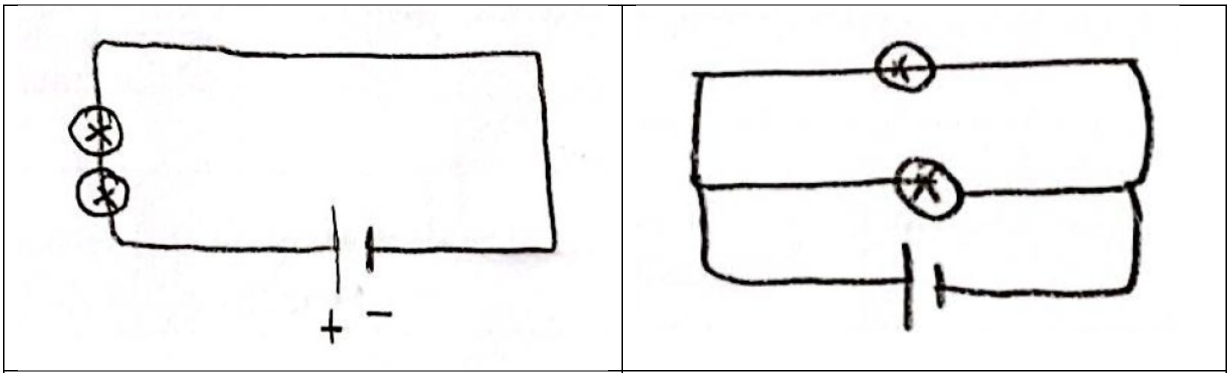
Figure 2. Drawing of ID24

ID24's explanation: The bulbs in a series circuit shine more because the power in the parallel circuit is split.

As it is seen from Figure 2, ID24 could correctly draw circuits in series and parallel; however, her understanding included errors like parallel-connected bulbs shining less due to splitting power. According to ID24's explanation, she did not take equivalent resistance into account in an electrical circuit and reached the wrong conclusion.

Category 3: Correct Drawing with Correct Answer, Including Lack of Explanation (The Moderate Level)

Six of the PSTs (23 %), ID1, ID3, ID4, ID5, ID9, and ID22, were able to draw the circuits with series and parallel correctly, and knew that the parallel circuit's bulbs' bulb brightness is more than the bulbs in the series. However, these students' explanations were correct up to some point and included some deficiencies. One of the drawings and answers (ID1) belonging to this category is presented in Figure 3.



circuit in series	circuit in parallel

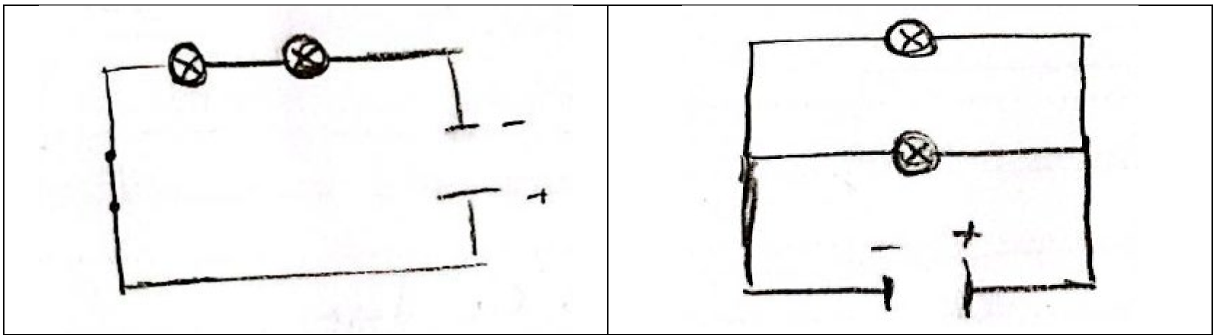
Figure 3. Drawing of ID1

ID1's explanation: The bulbs in the parallel-connected circuits shine more because the current in the series-connected circuit is shared by the bulbs. The bulbs in the parallel-connected circuits get more electricity, so they are brighter.

In her explanation, ID1 had a correct drawing and was able to link the amount of current and bulb brightness. She also knew the current is less in the circuit having bulbs connected in series. However, she could not explain why the bulbs in the parallel-connected circuits get more current and shine more. Therefore, her understanding of the core idea was correct to some extent and coded under the moderate level in terms of content knowledge.

Category 4: Correct Drawing and Explanation (The high level)

Only two of the participants (7 %), ID8 and ID18, were able to draw and explain the series and parallel circuits and correctly compare the bulbs' brightness in different types of circuits (series vs. parallel). When these two participants explained why the bulbs in the parallel circuits shine more, they referred to the voltage, unlike the participants labelled in the first three categories. ID8's drawings and explanation are presented in Figure 4:



circuit in series	circuit in parallel

Figure 4. Drawing of ID8

ID8's explanation: In the circuits connected in series, the bulbs share the same voltage because the bulbs are on the same row. However, in the parallel connected circuits, the voltage is the same in different ways, and the bulbs in the parallel circuits receive the same voltage.

In this explanation, ID8 explained the difference in the bulb brightness, referring to the difference between the voltage in series and parallel connection. Although this explanation is correct and labelled as a correct drawing and explanation, still, these two participants labelled in this category did not refer to resistance and equivalent resistance concepts. However, when we compared these two participants' responses to the previous categories, we can still claim that their knowledge is better than the first three categories in terms of scientific knowledge.

To sum up, participants' content knowledge results showed that only two of the 26 PSTs (7 %) could successfully draw and explain the difference in bulb brightness between parallel and series-connected circuits. The remaining participants (93 %) had either insufficient or false knowledge regarding the core idea (i.e., comparison of the bulb brightness between series and parallel connected circuits).

Findings for Personal Pedagogical Content Knowledge

Using the PCK mapping approach, we revealed individual PCK components and the interactions between PCK components representing their pPCK for each participant by examining their teaching plans. Analysis results showed that participants used knowledge of instructional strategies (KOIS) 43 times, knowledge of curriculum (KOC) 38 times, knowledge of students' understandings (KOL) 12 times, and knowledge of assessments (KOA) only 3 times. These findings suggest that PSTs built their pPCK on KOIS and KOC. Accordingly, they focused on instruction in their plan, so they used KOIS regularly, and also focused on teaching the objective/ core idea that was the comparison of bulb brightness between different types of circuits, so they used KOC. On the other hand, participants mainly ignored students' prior knowledge, potential difficulties, and possible misconceptions in their teaching plan, so the use of KOL was limited. Similarly, the participants did not focus on how they could check and detect students' understanding in their plans; therefore, KOA was the most limited PCK component in this study.

In-depth analysis of PCK also provided information about the interactions between PCK components. The study revealed that the interaction between KOIS and KOC was at most. The total number of interactions between these two components was 35. On the other hand, other interactions were limited. The second most observed interaction was between KOIS and KOL; this interaction was observed 7 times. Except for these interactions, nearly no interaction was observed between PCK components. Accordingly, there were two interactions between KOL and KOA, and two interactions between KOC and KOL. Furthermore, three different PCK components, which are KOC, KOIS, and KOL, interacted once in ID9's teaching plan. Examples of the interactions identified in this study and the evidence for the interactions between PCK components are presented in Table 1.

Table 1. *Examples of Interactions Among PCK Components Identified in Psts' Teaching Plans*

PST	Excerpt	Evidence for interaction	Interaction
ID1	Water flows in water pipes and fills the small pools. Pools connected in parallel get more water one by one, so the pools fill earlier. Water is shared in the pools connected in series, and they will fill less.	Water pipe and pool analogy to teach electricity- KOIS Comparison of parallel and series connection or teaching core idea-KOC	KOIS-KOC
ID6	Instead of saying this bulb shines more or less, I prefer them to conduct an experiment and make an inquiry. So, they learn by experiencing.	The use of experiment and inquiry as an instructional strategy- KOIS Students' active learning as a response to the teaching strategy-KOL	KOIS-KOL
ID13	Before experimenting, the teacher asks students which circuit's bulbs shine more. In this way, the teacher learns students' prior knowledge.	Asking questions about the bulb brightness before the activity- KOA Eliciting students' prior knowledge through questions- KOL	KOL-KOA
ID16	I bring materials into the class to get students' attention. Their motivation increases in this way.	Using materials- KOC Increasing student attention and motivation –KOL	KOC-KOL
ID9	I set circuits in series and parallel and experiment. I make the topic concrete to facilitate students' learning.	Teaching the core idea- KOC Making the experiment-KOIS Making the topic concrete to facilitate learning-KOL	KOC-KOIS-KOL

These findings suggest that KOIS and KOC were central in PSTs' pPCK based on their teaching plan of electricity. However, the other two PCK components, which are KOL and KOA, were mainly ignored and not considered in PSTs' plans. Therefore, it can be concluded that participants did not have strong pPCK depending on the analysis of the PCK mapping approach. While PSTs focused on the integration of the teaching instruction (i.e., KOIS) and the core idea (i.e., KOC) in their teaching plan, they disregarded possible students and their characteristics (i.e., KOL) and checking students' understanding in their potential teaching (i.e., KOA).

Findings for The Connection Between Content Knowledge and pPCK

The core idea of the study, which was the comparison of the bulb brightness between parallel and series circuits, was used to connect participants' content knowledge and pPCK. Participants' teaching plans (pPCK) were categorized based on participants' use of the core idea in their plan. This categorization yielded three different categories, namely personal PCK, general pedagogical knowledge (PK), and pseudo-PCK. First, the teaching plan was categorized as personal PCK if the participants accurately used the core idea in their teaching plan. Second, the teaching plan was categorized as general pedagogical knowledge (PK) if the participants did not use the core idea in the teaching plan and just focused on the general teaching without any specific emphasis on content knowledge. Third, their teaching plan was categorized as pseudo-PCK if participants inappropriately used the core idea, including misconceptions or inaccurate knowledge in their plan.

Hierarchically, personal PCK is better than general PK and general PK is better than pseudo-PCK because personal PCK promises better teaching as it has accurate content knowledge in the teaching plan. General PK promises nothing in terms of students' learning because it does not include any scientific content in teaching. Pseudo-PCK seems to be harmful for teaching and learning, as it leads to inaccurate knowledge. For example, if students are exposed to a teaching instruction including pseudo-PCK, students most probably would learn inaccurate information, and the causes of their difficulties and misconceptions would be that instruction and their teacher.

Findings for personal PCK showed that only two participants, ID8 and ID18, had personal PCK (7 %). These two participants correctly and explicitly included the core idea (comparison of the bulb brightness between parallel and series-connected circuits) in their teaching plan. The interactions were between KOC, KOIS, and KOL in these participants' teaching plans. The most observed interaction was between KOIS and KOC. The average number of interactions for each participant in the personal PCK category was 3.5. An example coding for the personal PCK category is presented below. In the given excerpt, the participant's teaching plan (i.e., excerpt) is presented. After the excerpt, the PCK codes and their interactions are shared. Then, why this participant's teaching plan was coded as personal PCK is explained:

ID 8's Teaching Plan

When I teach the content, I explain each concept at the beginning. Specifically, I focus on voltage and current differences. After talking about electric current over cables, I will explain the parallel and series connections. I tell them the bulbs share the same voltage in the series-connected circuit, as the bulbs are on the same line. However, the parallel connected bulbs get the same voltage, as each parallel line gets the same voltage. As a result, the bulbs in the parallel circuit shine more than the bulbs in the series. At the end of the lesson, I get students to set their circuits through online simulation tools.

Analysis of ID 8's teaching plan in terms of pPCK: ID 8' teaching plan was coded considering the interactions among PCK components. The codes are as follows:

"When I teach the content, I explain each concept at the beginning. Specifically, I focus on voltage and current differences. "

- KOC-KOIS interaction because content including voltage and current refers to KOC, the aim of teaching that content refers to KOIS.

"After talking about the electricity current movement over cables, I will explain the parallel and series connection. "

- KOC-KOIS interaction because parallel and series connection refers to KOC, talking about electrical movement, and explaining the circuit types refers to KOIS.

"At the end of the lesson, I get students to set their circuits through online simulation tools."

- KOC-KOIS interaction because setting electrical circuits refers to KOC, and using simulation tools addresses the KOIS.

After the analysis of these interactions, we summed the interactions to create ID8's PCK map. In conclusion, ID8's PCK map included 3 KOC-KOIS interactions. The analysis did not end here. As the final step of the analysis, we noticed whether this plan refers correct and explicit teaching of the content (parallel and series connection). As the participant's teaching plan included a correct explanation of the content (e.g., I tell them the bulbs share the same voltage in the series connected circuit as the bulbs are on the same line. However, the parallel connected bulbs get the same voltage, as each parallel line gets the same voltage. As a result, the bulbs in the parallel circuit shine more than the bulbs in the series. ID 8' PCK was coded as personal PCK.

The second category was general pedagogical knowledge (PK). The findings showed that 11 participants (42 %) were in this category: ID2, ID3, ID6, ID13, ID15, ID16, ID20, ID21, ID22, ID23, and ID26. This showed that 11 participants did not explicitly use the core idea in their teaching plan. All of the PCK components were used at least once for the interactions in this category. Similar to the personal PCK group, the most used interactions between PCK components were among KOC and KOIS. The average number of interactions between PCK components in the general PK category was 2. An example of coding for general pedagogical knowledge is given below. In this coding, first, ID 3' teaching plan is presented. Second, how his plan was coded by using PCK mapping is shared. In the last, why his teaching plan was coded as general pedagogical knowledge is explained:

ID 3's Teaching Plan

By using the simple electricity components, I construct the circuits. When the circuits work properly, students will see which bulbs shine more. The batteries' voltage will be the same, and the bulbs will be identical. Then, I use the online sources to show the results again, and I ask students to set up their experiments.

Analysis of ID3's teaching plan in terms of pPCK: Interactions between PCK components for the ID3's teaching plan are presented as follows:

"By using the simple electricity components, I construct the circuits. When the circuits work properly, students will see which bulbs shine more. "

- KOC-KOIS interaction was detected because the participant addressed the curricular goal that is the comparison of bulbs from different circuits, so he used KOC, and she used making an experiment as an instructional strategy, so he aimed to use KOIS.

"I use the online sources to show the results again, and I ask students to set up their experiments."

- In this example, again, KOC-KOIS interaction was identified as the participant aimed to show the results (comparison of different bulbs from different electric circuits) using KOC, and used online sources as an instructional strategy, showing his KOIS.

In total, ID3 used 2 KOC-KOIS interactions in his PCK map, depending on his teaching plan. Then, we looked for the content accuracy of his teaching plan. In his teaching plan, he did not mention accurate or inaccurate content knowledge. For example, he did not explicitly tell which bulb would shine more. Therefore, ID3's teaching plan did not reach the pPCK, and it was coded as general PCK.

Pseudo-PCK results showed that half of the participants' teaching plans were in this category. Accordingly, 13 PSTs (50 %), ID1, ID4, ID5, ID7, ID9, ID10, ID11, ID12, ID14, ID17, ID19, ID24, and ID25, used inaccurate knowledge about the core idea in their teaching plan. KOC, KOIS, and KOL were used for the interactions in the pseudo-PCK category. Again, the most used interaction was between KOC and KOIS. The average number of interactions for each participant in the pseudo-PCK category was 1.5. An example of coding for the pseudo-PCK is presented below. In this example, first, ID 12's teaching plan is presented. Then, the coding of the interactions among PCK components is presented. At the end, why her teaching plan was coded as pseudo-PCK is warranted.

ID 12's Teaching Plan

First of all, I tell primary school students that the bulbs in the series shine more than the bulbs in the parallel circuits. I will show this situation by designing an experiment. The bulbs in the series shine more because the bulbs are arranged side by side, and the current passes in the same direction. The current is divided in different ways in the parallel circuit; therefore, the bulbs shine less in the parallel circuit. After presenting students with the circuit materials to conduct their experiments, they can experiment and understand using the series and parallel connected circuits. Using some daily examples, students can understand the abstract topic. For example, in one case, the water is only used for the kitchen, and in another case, the same water is used for both the kitchen and bath. As the use of water increases, the power of the water decreases. Using this direct proportion, this example can be integrated and compared to the bulb brightness in different circuits.

Analysis of ID 12's teaching plan in terms of pPCK: The PCK mapping approach was used to reveal ID 12's PCK map, including the interactions among PCK components. The interactions are as follows for this participant:

"I tell primary school students that the bulbs in the series shine more than the bulbs in the parallel circuits. I will show this situation by designing an experiment."

- KOC-KOIS interaction was detected as the bulbs in different circuits refer to the objective (KOC), and the participant used experimentation as the specific instructional strategy (KOIS).

"The bulbs in the series shine more because the bulbs are arranged side by side, and the current passes in the same direction. The current is divided in different ways in the parallel circuit; therefore, the bulbs shine less in the parallel circuit."

- KOC-KOIS interaction was detected because the participant explained the learning objective. Emphasis on learning objective refers to KOC, and the direct instruction of the objective is KOIS.

"After presenting students with the circuit materials to conduct their experiments, they can experiment and understand using the series and parallel connected circuits."

- KOL-KOIS interaction was identified. Experimenting refers to the KOIS, and the increase of students' understanding in response to the experiment refers to the KOL.
- Using some daily examples, students can understand the abstract topic. For example, in one case, the water is only used for the kitchen, and in another case, the same water is used for both the kitchen and bath. As the use of water increases, the power of the water decreases. Using this direct proportion, this example can be integrated and compared to the bulb brightness in different circuits.
- KOL-KOIS instruction was identified. The use of examples and analogies refers to KOIS, and an increase in students' understanding addresses the KOL component.

After revealing the interactions in ID 12's teaching plan, we summed the frequency of each interaction, and this formed ID 12's PCK map that includes 2 KOC-KOIS and 2 KOL-KOIS interactions. After that, we examined whether her teaching plan included accurate or inaccurate content knowledge. As it is seen from her teaching plan, she presented erroneous ideas regarding the comparison of the bulb brightness in different circuit connections. For example, she thought the bulbs in the series connections shine more than the bulbs in the parallel circuits. Because of her false teaching plan, ID 12's PCK was coded as pseudo-PCK, which is a threat to her future teaching.

Summary of these three PCK categories derived from the use of the core idea in the teaching plan shows that KOIC and KOIS interaction is central in all three PCK emerged in this study. Likewise, the average number of interactions between PCK components was similar in the three different PCK categories. Therefore, just looking at the interactions among PCK components or counting the number of interactions among PCK components seems to be deceptive in understanding PCK. Thanks to the use of the core idea, these three different PCK categories have been identified. Identification of these three PCK categories revealed a hierarchical classification in terms of teaching for these categories. Accordingly, personal PCK includes the correct use of the core idea, so it promises high-quality teaching. General PK does not provide correct teaching of the core idea, but also does not present wrong information, so it is useless in teaching. Pseudo-PCK produces wrong content knowledge about the core idea, so it seems to be harmful for teaching.

After revealing three different PCK categories based on the use of core idea, we matched participants' content knowledge with these PCK categories, and the following table was formed (Table 2). This table summarizes the connection between content knowledge and pPCK:

Table 2. *Connection Between Content Knowledge and pPCK*

CK vs. PCK	Completely Incorrect CK	Correct Drawing Incorrect Answer and Explanation	Correct Drawing, Correct Answer Incomplete Explanation	Completely Correct CK
Personal PCK	X	X	X	ID8, ID18
Generic PCK	ID13, ID15, ID20, ID21	ID2, ID6, ID16, ID23, ID26	ID3, ID22	X
Pseudo PCK	ID11, ID12, ID17, ID19, ID25	ID7, ID10, ID14, ID24	ID1, ID4, ID5, ID9	X

Table 2 shows that pPCK, which shows high-quality teaching, also requires strong content knowledge. Two of the 26 PSTs who participated in the study knew the core idea and were able to transform their content knowledge for teaching. However, the rest of the participants who did not know the content or had deficient knowledge in the core idea did not reach to pPCK category. When these participants' teaching plans were examined, these PSTs either did not reflect content knowledge in their plan and so used general PK, or they inaccurately used content knowledge in their teaching plan, producing pseudo-PCK. In total, 24 of the 26 participants did not know the content knowledge and consistently had general PK or pseudo-PCK. Therefore, it can be concluded that participants had limited content knowledge in electricity, and their teaching quality was low.

Conclusion and Discussion

A strong PCK should be rich in terms of individual components (e.g., KOIS), and their interactions (e.g., KOIS-KOL) (Park & Chen, 2012). However, in this study, mainly KOIS and KOC interactions were observed, and other two components' interactions were limited in the participants' teaching plan. Therefore, participants' pPCK was not strong. Similarly, Ottogalli and Bermudez (2024) conducted a study with faculty members on biodiversity topics and reported that KOA was not integrated into the PCK maps of the participants. In another study, Reynolds and Park (2021) compared PSTs' educative teacher performance with PCK and reported that participants focused on the consistency between curricular objectives and the instructional strategy when there is an interaction between KOC and KOIS. Similar to this situation, participants in this study focused on teaching the core idea in their teaching plan, and they addressed specific instructional strategies to convey the core idea that students can understand. Their focus on the core idea, which looks like the curricular objective, and the corresponding instructional strategy made KOIS-KOC interactions central to this study. On the other hand, Reynolds and Park (2021) reported that KOC is mainly ignored in the faculty of education programs, so the centrality of the KOC is surprising for this study. The structure of the study can be the reason for such a result. In this study, we presented the core idea or objective to the PSTs before they prepared their teaching plan. Therefore, any use of this core idea was accepted as evidence for the KOC, making this component central for the interactions among PCK components. However, the other two components, which are KOL and KOA, were not noticed in their plans.

The lack of interaction for the KOL and KOA can be caused by participants' insufficient KOL and KOA. For example, Demirdöğen et al. (2016) reported that KOL develops with experience, and PSTs do not have developed KOL. Similarly, participants in this study did not have any teaching experience, and they were not familiar with students' understandings, so they did not use KOL and get it interact with other PCK components very much. In line with this, Chan (2022) claimed key components of the PCK are KOIS and KOL, and they are indicators of effective teaching. Therefore, a strong PCK should be set on the interactions of these two components. Also, KOL is directly linked with content knowledge because if teachers know the content knowledge, they can identify students' difficulties and misconceptions better (Park & Oliver, 2008). On the other hand, most of the participants in this study did not know the core idea very well; therefore, it is not surprising that participants had limited KOL. As a result, regarding the importance of the KOL, the participants should improve KOL as an initial step to have strong pPCK.

Another component that PSTs were weak in this study was KOA. The reason why participants did not have strong assessment knowledge can be related to the lack of emphasis in education faculty programs. For example, Sickel and Friedrichsen (2018) reported that teachers' KOA improves if there is an emphasis on the assessment in the teacher education programs. Participants' weakness about the KOA is not unique to this study, and it is not related to their experience level. Accordingly, Padilla and van Driel (2011) reported that even university professors teaching quantum had limited KOA and focused on the summative assessments, ignoring formative assessment. Therefore, the lack of KOA seems to be a universal problem for the PCK researchers. Therefore, teachers should focus on their assessment and find ways to improve their assessment for better teaching.

Next, the study showed that both participants' content knowledge and pPCK limited. When content knowledge is limited, insufficiency of pPCK is expected because content knowledge is part of professional knowledge bases, and if it does not improve, PCK becomes limited (Carlson & Daehler, 2019). One of the causes of limited content knowledge and pPCK can be PSTs' formal education because PCK improves through formal education where both content knowledge and KOIS are learnt (Mthethwa-Kunene et al., 2015). Therefore, the quality of teacher education programs should improve. The second cause explaining participants' limited content knowledge and pPCK can be the program they are enrolled. Accordingly, participants were primary school PSTs. Although content knowledge is not emphasized in the primary level education, the centrality of content knowledge increases with students' increasing age and cognitive level in the higher grade levels, like secondary education. Therefore, what teachers teach significantly affects their content knowledge and pPCK. In line with this explanation, Pitjeng-Mosabala and Rollnick (2018) reported that when teachers attended professional development programs, teachers teaching content knowledge directly at high grade levels improved their PCK more than other teachers teaching lower grades. Similarly, Park et al. (2020) compared USA and South Korea teachers' PCK in the photosynthesis topic and found that high school teachers' PCK scores were higher than middle school teachers' PCK. In another study, Kirschner et al. (2016) examined physics teachers' PCK and reported that teachers teaching at upper grade levels had higher PCK scores. To sum up, the grade level that teachers are assigned for teaching matters, and it affects PCK. Therefore, primary school teachers, including PSTs, should be supported to improve both their content knowledge and pPCK.

In this study, only 2 participants' PCK reached pPCK, which is desired; on the other hand, 24 of them did not reach this level. The main difference between these students seems to be their differing content knowledge. As students have the correct content knowledge, they do not have difficulty in integrating this content knowledge into their teaching plan. On the other hand, the ones who had difficulty in understanding the content knowledge also had difficulty in preparing a teaching plan about that content. As this is not an experimental study, we can not be sure that the only factor causing the difference in the pPCK was their different content knowledge. Maybe, participants' differences also affect their pPCK. For example, the ones who are interested in physics and electricity might be more knowledgeable about the topic, so they might reflect their positive attitude and content knowledge in their teaching plan. Likewise, the participants who reached pPCK might have family members who were interested in physics, so these participants might be more familiar with the electricity topic, and could better integrate their knowledge into their teaching plan. On the other hand, the participants' undergraduate education most probably does not explain the difference in their pPCK because each participant got the same science and science education courses at the same time.

The way of measurement for PCK might also affect the results. Our participants' pPCK results are pure, and no scaffolding was used that could amplify their PCK. In other words, as we aimed to see the actual situation, we did not assist the participants. If such scaffolds had been used, participants' pPCK results would probably have been better. For example, we could have used the CoRes (content representation tools) that was developed to connect big ideas and pedagogy (Nilsson & Karlsson, 2019) to assess participants' pPCK. However, in the end, the CoRes is a scaffold, and it facilitates teachers' planning. The same teacher's lesson plan can change when the CoRes is used or not. If the CoRes is used, the results would be better as the teacher is assisted. To sum up, the study's PCK findings were not contaminated by additional support provided to the participants, and the results of the participants' PCK represent their actual teaching plan. The measurement problem was also addressed by Chan (2022) as a task structure effect. Accordingly, Chan (2022) reported that the ways of PCK measurement are different. While one researcher asks questions about the interactions between PCK components, another researcher does not. Most probably, the number of interactions will be higher in the first researcher's study because the interview questions are directly linked to the possible interactions among PCK components. Therefore, PCK measurements should be standardized to increase the validity and reliability of findings and compare different studies' results.

The main findings of the study are about the connection between content knowledge and pPCK. The study yielded three different PCK and content knowledge determines hierarchy between these PCK categories. Accordingly, PSTs having a solid understanding of the topic could reflect their content knowledge in their plans, and generate pPCK that promised high-quality teaching. However, some of the PSTs who did not know the content did not mention the content knowledge in their plan and focused on pedagogical issues. Their lack of emphasis on content knowledge in the teaching plan showed these PSTs had general pedagogical knowledge (PK). As PSTs did not mention the content knowledge in their plan, these teachers' knowledge does not bring high-quality teaching. Some of the PSTs, who did not know the content, used inaccurate content knowledge in their teaching plan, such situations were named as pseudo-PCK. Pseudo-PCK seems to be harmful for effective teaching, as it includes inaccurate content knowledge and potentially misleads students in learning. Therefore, these three PCK categories can be hierarchically sorted from the highest level to the lowest as pPCK, general PK, and pseudo-PCK. Similar to this study, Veal and MaKinster (1999) offered a PCK model that connected content knowledge and PCK. According to this model, teacher knowledge is hierarchical. The lowest level is pedagogical knowledge (e.g., teaching method, planning, evaluation). This knowledge is not related to content knowledge. The pedagogical knowledge is similar to the general PK offered in this study. After having pedagogical knowledge, the teachers improve their general PCK, which is more specific than pedagogical knowledge and specific to a discipline like science and math. Veal and MaKinster (1999) compare general PCK as orientation towards science components of the Magnusson model. Then, general PCK becomes more specific by forming domain-specific PCK. A teacher's PCKs in different domains of the same disciplines are examples of domain-specific PCK (PCK in physics in science, PCK in chemistry in science). Hierarchically, the most specific and developed type of PCK is topic-specific PCK. Previous PCK levels are a prerequisite for having a topic-specific PCK. Accordingly, each topic in a domain (e.g., electricity, force, and motion) has its own teaching style, method, and approach for effective teaching, and this makes PCK topic-specific. pPCK proposed in this study is similar to the topic-specific PCK offered by Veal and MaKinster (1999) because pPCK and topic-specific PCK focus on teaching specific content knowledge accurately.

Similar to Veal and MaKinster (1999), Schiering et al. (2023) proposed four hierarchical PCK levels in physics. In the lowest level, level 1, the teacher has basic knowledge, which can be content-specific or nonspecific. In level 2, PCK starts forming, but it is limited. In level 3, the teacher knows misconceptions and strategies in a specific topic. At the highest level, level 3+, the teacher justifies his instructional strategy, uses assessment, and designs his lesson based on knowledge of students' understandings (KOL). While level 1 is similar to the general PK in this study, level 3+ is similar to the pPCK of this study, as both of them promise high-quality teaching. Although some clues have been identified for general PK and pPCK from the literature, no study was found related to pseudo-PCK. This situation can be related to what researchers understand about PCK. Starting from Shulman, PCK has been matched with high-quality teaching. Therefore, potential teaching related to low-quality teaching was not considered as PCK in previous research. If we think PCK is an indicator of high-quality teaching, then pseudo-PCK is not an actual form of PCK, as it results in low-quality teaching. Even though we do not accept pseudo-PCK as an actual form of PCK, our observations showed that half of the participants suffered from it. Whether pseudo-PCK is real or unreal, the researchers should solve problems that emerge from pseudo-PCK to avoid potential low-quality teaching. Therefore, the first step for high-quality teaching and solid pPCK seems to be coping with pseudo-PCK challenges.

Pseudo-PCK mainly results from teachers' or PSTs’ naïve understandings of the content knowledge. As they do not know the content, they cannot teach it, and they suffer from pseudo-PCK. The primary goal of science education is to produce scientifically literate students. One common characteristic of a scientifically literate person is having a grasp of content knowledge. However, if future primary school PSTs are not scientifically literate, do not know the content, teach wrong knowledge, and use pseudo PCK, how could our country raise scientifically literate generations in the future? At this point, the faculty of education programs in preparing teachers becomes crucial. The teacher education programs for the lower grade levels mainly ignore content knowledge in their programs. The reasons for this can be limited content knowledge of educators, the belief that advanced knowledge is not necessary for primary school programs, and the belief that primary school PSTs can not understand the science content knowledge because of their limited science background. If these reasons are eliminated from teacher education programs, the rate of pseudo-PCK might decrease, and the teaching quality can be high in future primary school science classes. The first solution can be improving science educators’ content knowledge. In this way, they could better monitor PSTs’ content knowledge and eliminate misconceptions that increase PSTs’ content knowledge and decrease the rate of possible pseudo-PCK. Second, we should change our beliefs about primary school education programs. Some may think that content knowledge is not important in primary school. On the contrary, content knowledge might be the most important at the primary school level because science education starts in the primary school level, and the students will construct their all new learning on this knowledge. Therefore, a solid foundation is needed for the primary school level, and the PSTs we raise in the teacher education program should have such knowledge and be capable of teaching it. Lastly, some may believe that primary school PSTs can not learn the correct knowledge as their science background is limited. This dangerous approach directly contradicts contemporary educational views. Today, we believe that every individual can improve themselves if they are supported and study hard. Therefore, we should support primary school PSTs and their content knowledge and encourage them to improve their content knowledge and teaching. It should not be forgotten that the main role of faculty staff is to scaffold PSTs in teacher education programs.

Implications and Limitations

The study has implications for researchers and education faculty. First, researchers can use the theoretical framework of this study in their PCK research. In this study, three PCK models, including the Magnusson model, PCK mapping approach, and refined consensus model, were used. If the future research uses these PCK models together, the theoretical part of these studies will be comprehensive, and the explanatory power of their research will be high.

Second, this study supports a positive relationship between content knowledge and pPCK, and provides 3 different PCK categories. The researchers can use these three PCK categories in their research and propose mechanisms explaining the relation between content knowledge and pPCK. Likewise, using the same analysis method of this study, researchers can identify their participants’ pPCK, general PK, and pseudo-PCK.

Third, this study showed that when only one core idea is used, the connections between content knowledge and pPCK are identified more easily. Researchers can also focus on only one core idea instead of focusing on one unit or a few core ideas to better see the connections between content knowledge and pPCK.

Fourth, researchers can observe real science classes considering the three PCK categories that emerged in this study. The researchers can focus on the evidence of what happens in class in terms of learning and teacher-student interactions when these three PCK categories are identified. In this way, the link between PCK and practice can be clarified.

Fifth, we did not find any difference in terms of the individual PCK components, the types of interactions among PCK components, and the number of interactions among PCK components when we compared the three PCK categories. The only difference was how content knowledge was used in the teaching plan. Researchers can examine whether PCK components, their interactions, and the number of interactions change between different PCK categories (e.g., pPCK vs. pseudo-PCK). In this way, these PCK categories can be directly and the nature of PCK indirectly can be better understood.

Sixth, previous research did not emphasize pseudo-PCK. This pseudo-PCK may not be an actual PCK; however, it is an indicator of low-quality teaching, and it exists in teachers' plans, and probably in science classes. For example, half of the participants' teaching plan included pseudo-PCK in this study. Therefore, researchers can specifically focus on the pseudo-PCK, identify teachers' pseudo-PCK, and develop and apply treatments or PD programs to ameliorate pseudo-PCK. In this way, low-quality teaching can be eliminated, which can be the first step for high-quality teaching.

The study also has implications for the primary education programs in the education faculties. The findings showed that primary school PSTs did not know the difference in bulb brightness between circuits connected in parallel and series. Similarly, they did not know how they could teach this core idea. Therefore, primary school PSTs' both electricity content knowledge and topic-specific PCK in electricity should be improved. Specifically, participants' knowledge of students' understandings and knowledge of assessment was limited. Therefore, the number of courses about assessments can be increased to improve PSTs' assessment knowledge. Likewise, PSTs can have more opportunities that meet PSTs with real students. In this way, they could be familiar with students' prior knowledge, difficulties, and misconceptions, improving their knowledge of students' understandings.

The study also had five main limitations. First, there are three realms of PCK according to the refined consensus model. We focused on pPCK in this study. The future studies can also focus on ePCK and cPCK. In this way, content knowledge and PCK relation can be better understood. Second, we did not focus on the learning context in this study, as the learning context makes it difficult to see the connections between content knowledge and PCK. The future studies can also include learning context in their research. Such research can be more difficult to carry out and analyze, but will also be comprehensive and can provide more detailed and accurate information about the content knowledge and PCK relationship, considering the role of learning context. Third, PCK has three phases, including pre-active phase, interactive phase, and post-active phase. In this study, we focused on the pre-active phase by using participants' teaching plans. The future studies can include interactive and post-active phases in their PCK research, so they could better understand the connection between content knowledge and PCK. The fourth limitation of the study is about data collection. In this study, we asked one question to assess content knowledge, and asked participants to prepare a teaching plan to assess their pPCK. If we asked more than one question to assess participants' content knowledge, we would get more reliable information regarding participants' content knowledge. For example, we would give the number of bulbs, batteries, and other circuit components in different questions, and we could better distinguish who knows the content more. The future research can ask a larger number of content knowledge questions to assess participants' content knowledge. Likewise, participants' teaching plans can be triangulated with the interviews in future studies. In this way, future studies' reliability and validity can improve. Lastly, this study is qualitative research, so the results obtained from the study can not be generalized to other PSTs. However, PSTs having similar characteristics to this study's participants (e.g., similar content knowledge level, being students at a private university, having difficulty teaching science topics) and their departments can benefit from the findings of the study.

Declarations

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References

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

Aydın, S., & Boz, Y. (2012). Review of studies related to pedagogical content knowledge in the context of science teacher education: Turkish case. *Educational Sciences: Theory and Practice*, *12*(1), 497-505.

Aydın, S., Boz, N., & Boz, Y. (2010). Factors that are influential in pre-service chemistry teachers' choices of instructional strategies in the context of methods of separation of mixtures: A case study. *The Asia-Pacific Education Researcher*, *19*(2), 251-270. https://doi.org/10.3860/taper.v19i2.1595

Ayvacı, H. Ş., Bebek, G., & Yamaçlı, S. (2023). Comparison of the theoretical and practical knowledge of the pre-service science teachers in Turkey: The context of simple electrical circuits. *Participatory Educational Research*, *10*(3), 130-149. https://doi.org/10.17275/per.23.48.10.3

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

Bartos, S.A., Lederman, N.G., & Lederman, J.S. (2014). Teachers' reflections on their subject matter knowledge structures and their influence on classroom practice. *School Science & Maths*, *114*(3), 125-138. https://doi.org/10.1111/ssm.12058

Boz, N., & Boz, Y. (2008). A qualitative case study of prospective chemistry teachers' knowledge about instructional strategies: introducing particulate theory. *Journal of Science Teacher Education*, *19*, 135-156. https://doi.org/10.1007/s10972-007-9087-y

Bravo, P., & Cofré, H. (2016). Developing biology teachers' pedagogical content knowledge through learning study: the case of teaching human evolution. *International Journal of Science Education*, *38*(16), 2500-2527. https://doi.org/10.1080/09500693.2016.1249983

Canbazoğlu, S., Demirelli, H., & Kavak, N. (2010). Investigation of the relationship between pre-service science teachers' subject matter knowledge and pedagogical content knowledge regarding the particulate nature of matter. *Elementary Education Online*, *9*(1), 275-291. http://ilkogretim-online.org.tr

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

Carpendale, J., & Hume, A. (2019). Investigating practising science teachers' pPCK and ePCK development as a result of collaborative CoRe design. In A. Hume, R. Cooper, & A. Borowski (Eds.), *Repositioning pedagogical content knowledge in teachers' knowledge for teaching science*, (pp. 225-252). Springer. https://doi.org/10.1007/978-981-13-5898-2_10

Chan, K. K. H. (2022). A critical review of studies using the pedagogical content knowledge map approach. *International Journal of Science Education*, *44*(3), 487-513. https://doi.org/10.1080/09500693.2022.2035011

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

Coe, R., Aloisi, C., Higgins, S., & Major, L. E. (2014). What makes great teaching? Review of the underpinning research. https://www.suttontrust.com/wp-content/uploads/2014/10/What-Makes-Great-Teaching-REPORT.pdf

de Jong, O. & van Driel, J. (2004). Exploring the development of student teachers' pck of the multiple meanings of chemistry topics. *International Journal of Science and Mathematics Education*, *2*, 477-491. https://doi.org/10.1007/s10763-004-4197-x

Demirdöğen, B., Hanuscin, D. L., Uzuntiryaki-Kondakci, E., & Köseoğlu, F. (2016). Development and nature of preservice chemistry teachers' pedagogical content knowledge for nature of science. *Research in Science Education*, *46*, 575-612. https://doi.org/10.1007/s11165-015-9472-z

Gess-Newsome, J. (2015). A model of teacher professional knowledge and skill including PCK: Results of the thinking from the PCK Summit. In Berry, A., Friedrichsen, P., & Loughran, J. (Eds.), *Re-examining pedagogical content knowledge in science education* (pp. 38-

52). Routledge. https://doi.org/10.4324/9781315735665-8

Henze, I., & van Driel, J. H. (2015). Toward a more comprehensive way to capture PCK in its complexity. In Berry, A., Friedrichsen, P., & Loughran, J. (Eds.), *Re-examining pedagogical content knowledge in science education* (pp. 120-134). Routledge.

Irmer, M., Traub, D., Böhm, M., Förtsch, C., & Neuhaus, B. J. (2023). Using video-based simulations to foster pPCK/ePCK—new thoughts on the refined consensus model of PCK. *Education Sciences*, *13*(3), 261. https://doi.org/10.3390/educsci13030261

Kapyla, M., Heikkenen, J., & Asunta, T. (2009). The influence of content knowledge on pedagogical content knowledge a case of teaching photosynthesis and plant growth. *International Journal of Science Education*, *31*(10), 1395 - 1415. https://doi.org/10.1080/09500690802082168

Kaya, O. N. (2009). The nature of relationships among the components of pedagogical content knowledge of preservice science teachers: 'Ozone layer depletion' as an example. *International Journal of Science Education*, *31*(7), 961-988. https://doi.org/10.1080/09500690801911326

Kind, V. (2009). A conflict in your head: An exploration of trainee science teachers' subject matter knowledge development and its impact on teacher self confidence. *International Journal of Science Education*, *31*(11), 1529–1562. https://doi.org/10.1080/09500690802226062

Kirschner, S., Borowski, A., Fischer, H. E., Gess-Newsome, J., & von Aufschnaiter, C. (2016). Developing and evaluating a paper-and-pencil test to assess components of physics teachers' pedagogical content knowledge. *International Journal of Science Education*, *38*(8), 1343-1372. https://doi.org/10.1080/09500693.2016.1190479

Lederman, N. G. & Gess-Newsome, J. (1992). Do subject matter knowledge, pedagogical knowledge, and pedagogical content knowledge constitute the ideal gas law of science teaching? *Journal of Science Teacher Education*, *3*(1), 16-20. https://doi.org/10.1007/BF02614732

Magnusson, S. J., Borko, H., & Krajcik, J. S. (1999). Nature, source, and development of pedagogical content knowledge for science teaching. In J. G. Newsome & N. G. Lederman (Eds.), *Examining pedagogical content knowledge: The construct and its implications for science education* (pp. 95–132). Kluwer Press. https://doi.org/10.1007/0-306-47217-1_4

Mapulanga, T., Ameyaw, Y., Nshogoza, G., & Bwalya, A. (2024). Integration of topic-specific pedagogical content knowledge components in secondary school science teachers' reflections on biology lessons. *Discover Education*, *3*(1), 17. https://doi.org/10.1007/s44217-024-00104-y

Merriam, S. B. (2009). *Qualitative research: A guide to design and implementation*. Jossey-Bass.

Mthethwa-Kunene, E., Onwu, G. O., & de Villiers, R. (2015). Exploring biology teachers' pedagogical content knowledge in the teaching of genetics in Swaziland science classrooms. *International Journal of Science Education*, *37*(7), 1140-1165. https://doi.org/10.1080/09500693.2015.1022624

Nilsson, P., & Karlsson, G. (2019). Capturing student teachers' pedagogical content knowledge (PCK) using CoRes and digital technology. *International Journal of Science Education*, *41*(4), 419-447. https://doi.org/10.1080/09500693.2018.1551642

Ottogalli, M. E., & Bermudez, G. M. (2024). A PCK-mapping approach to show the integration among components of the pedagogical content knowledge of elementary education teacher educators about biodiversity. *Teaching and Teacher Education*, *151*, 104746. https://doi.org/10.1016/j.tate.2024.104746

Özden, M., (2008). The effect of content knowledge on pedagogical content knowledge: The case of teaching phases of matters. *Educational Sciences: Theory and Practice*, *8*(2), 633-645.

Özmen, K. (2024). Health science students' conceptual understanding of electricity: misconception or lack of knowledge? *Research in Science Education*, *54*(2), 225-243. https://doi.org/10.1007/s11165-023-10136-3

Padilla, K., & van Driel, J. (2011). The relationships between PCK components: the case of quantum chemistry professors. *Chemistry Education Research and Practice*, *12*(3), 367-378. https://doi.org/10.1039/C1RP90043A

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

Park, S., & Chen, Y.C. (2012). Mapping out the integration of the components of pedagogical content knowledge (PCK): Examples from high school biology classrooms. *Journal of Research in Science Teaching*, *49*(7), 922-941. https://doi.org/10.1002/tea.21022

Park, S., & Suh, J. K. (2019). The PCK map approach to capturing the complexity of enacted PCK (ePCK) and pedagogical reasoning in science teaching. In A. Hume, R. Cooper, & A. Borowski (Eds.), *Repositioning pedagogical content knowledge in teachers' knowledge for teaching science*, (pp. 187-199). Springer.

Park, S., Choi, A., & Reynolds, W. M. (2020). Cross-national investigation of teachers' pedagogical content knowledge (PCK) in the US and South Korea: what proxy measures of teacher quality are related to PCK? *International Journal of Science Education*, *42*(15), 2630-2651. https://doi.org/10.1080/09500693.2020.1823046

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

Reynolds, W. M., & Park, S. (2021). Examining the relationship between the Educative Teacher Performance Assessment and preservice teachers' pedagogical content knowledge. *Journal of Research in Science Teaching*, *58*(5), 721-748. https://doi.org/10.1002/tea.21676

Schiering, D., Sorge, S., Keller, M. M., & Neumann, K. (2023). A proficiency model for pre-service physics teachers' pedagogical content knowledge (PCK)—What constitutes high-level PCK? *Journal of Research in Science Teaching*, *60*(1), 136-163. https://doi.org/10.1002/tea.21793

Sencar, S., Yılmaz, E. E., & Eryılmaz, A. (2001). High school students' misconceptions about simple electric circuits. *Hacettepe Üniversitesi Eğitim Fakültesi Dergisi*, *21*, 113-120.

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

Sickel, A. J. (2012). *Examining beginning biology teachers' knowledge, beliefs, and practice for teaching natural selection* [Unpublished doctoral dissertation]. University of Missouri.

Sickel, A. J., & Friedrichsen, P. (2018). Using multiple lenses to examine the development of beginning biology teachers' pedagogical content knowledge for teaching natural selection simulations. *Research in Science Education*, *48*, 29-70. https://doi.org/10.1007/s11165-016-9558-2

Stender, A., Brückmann, M., & Neumann, K. (2017). Transformation of topic-specific professional knowledge into personal pedagogical content knowledge through lesson planning. *International Journal of Science Education*, *39*(12), 1690-1714. https://doi.org/10.1080/09500693.2017.1351645

Uşak, M. (2009). Preservice science and technology teachers' pedagogical content knowledge on cell topics. *Educational Sciences: Theory & Practice*, *9*(4), 2033-2046.

Usak, M., Ozden, M., & Eilkıs, I. (2011). A case study of beginning science teachers' subject matter (SMK) and pedagogical content knowledge (PCK) of teaching chemical reaction in Turkey. *European Journal of Teacher Education Aquatic*, *34*(4), 407–429. https://doi.org/10.1080/02619768.2011.592977

Veal, W. R., & MaKinster, J. G. (1999). Pedagogical content knowledge taxonomies. *Electronic Journal of Science Education*, *3*(4), 1-17.