education sciences

MDPI

Article

Teacher Professional Development in Integrated STEAM Education: A Study on Its Contribution to the Development of the PCK of Physics Teachers

Iva Martins * and **Mónica Baptista**

Instituto de Educação, Universidade de Lisboa, 1649-013 Lisboa, Portugal; mbaptista@ie.ulisboa.pt
* Correspondence: ivamartins@edu.ulisboa.pt

Abstract: Integrated STEM education (iSTEM) has attracted attention due to its potentialities regarding students' learning and intentions to pursue STEM-related careers. However, although increasingly popular, iSTEM remains challenging and elusive, particularly from teachers' perspective. This scenario became even more complex with the inclusion of "A", from the Arts. Considering that the quality of teachers is decisive in the success of integrated STEAM education (iSTEAM), it is essential to provide teachers with opportunities to develop their Pedagogical Content Knowledge (PCK) for iSTEAM. In this work, the aim was to understand the effect of teacher professional development (TPD) within iSTEAM on the development of Physics teachers' PCK related to the topic of "Electrical circuits with associations in series and parallel". This study followed a pre-test/post-test design with a single group, which facilitates the subsequent comparison of participants' reported PCK before and after their involvement in the TPD. The results showed that the TPD had a favorable impact on teachers' PCK. The results of this study also contribute to defining a specific PCK for STEAM (STEAM-PCK).

Keywords: integrated STEM education; integrated STEAM education; PCK; physics teachers; teacher professional development

check for updates

Citation: Martins, I.; Baptista, M. Teacher Professional Development in Integrated STEAM Education: A Study on Its Contribution to the Development of the PCK of Physics Teachers. *Educ. Sci.* **2024**, *14*, 164. https://doi.org/10.3390/educsci14020164

Academic Editor: Jairo Ortiz-Revilla

Received: 4 December 2023
Revised: 28 January 2024
Accepted: 1 February 2024
Published: 5 February 2024

1. Introduction

In recent years, integrated STEM (Science, Technology, Engineering, and Mathematics) education (iSTEM) has attracted attention due to its potential regarding students' learning and intentions to pursue STEM-related careers. In the literature, several studies describe that iSTEM promotes students' motivation to follow STEM areas and the development of fundamental abilities such as the resolution of multidisciplinary real-world problems, critical thinking, collaboration, and creativity (e.g., [1,2]).

However, despite its increasing popularity, iSTEM remains challenging and elusive, particularly from teachers' perspective. Furthermore, the inclusion of the "A" (to encompass the fields of Arts and Humanities) has brought forth even more challenges. For example, similar to the discussions regarding iSTEM, issues about how various areas should be combined and the fundamental practices of this approach are also debated in integrated STEAM education (iSTEAM) (e.g., [3,4]), which is defined as a transdisciplinary approach that aims to solve real-world problems [5]. Nonetheless, the inclusion of the Arts is viewed as a comprehensive blend of disciplines that enhances specific skills and attitudes, such as creativity, critical thinking, and an innovative mindset [3].

Hence, and considering that the quality of teachers is decisive in the success of iSTEAM, they are faced with the need to develop the knowledge, skills, and confidence to implement this type of approach. According to the literature, many of the challenges that are faced by teachers stem from their limited training within their own subject disciplines [6,7], but teacher professional development (TPD) programs for in-service teachers are usually focused on one domain [8]. In this way, teachers reveal superficial knowledge and other limitations regarding integrated approaches like iSTEM and iSTEAM. More precisely, teachers exhibited constrained expertise in individual subjects or interdisciplinary knowledge, faced changes in adapting to different pedagogical approaches, encountered a shortage of time and proficiency in integrating curricula, and demonstrated a lack of familiarity with pertinent standards and assessments [9–13].

It is, therefore, crucial to provide teachers with training opportunities that allow them to enhance their skills, base knowledge, and experiences, thereby increasing their capacity and readiness to teach subjects through integrated approaches [14]. In other words, it is essential to create opportunities for teachers to develop Pedagogical Content Knowledge (PCK) that is suitable for iSTEAM.

However, there is a shortage of studies that correlate teachers' participation in teacher professional development (TPD) focused on iSTEAM with the development of their Pedagogical Content Knowledge (PCK). Additionally, as some studies are beginning to emerge on what constitutes STEM-PCK (e.g., [15,16]), it is also crucial to contribute to the body of knowledge that allows us to pave the way for defining what might constitute specific PCK for iSTEAM.

Taking these considerations into account, this study aims to shed light on teacher training models that are effective in developing teachers' PCK which, in turn, can contribute to understanding which components a STEAM-PCK should include. Specifically, our study aimed to understand the effect of TPD in iSTEAM on the development of Physics teachers' PCK related to the topic of "Electrical circuits with associations in series and parallel", and the following research questions (RQ) guided the study:

RQ1: What is the effect of TPD on the overall teachers' PCK?

RQ2: What is the effect of TPD on each PCK component?

2. Theoretical Background

2.1. Integrated STEAM Education

In recent decades, STEM education has played an increasingly significant role in international educational policies. This relevance stems largely from the need to motivate and recruit students for scientific careers to respond to the global competitiveness that societies face [2]. Additionally, the potential of STEM education also includes fostering students' curiosity about natural phenomena [17] and improving attitudes toward scientific areas, resulting in increased motivation and interest in these subjects [18].

Since its proposal, STEM education has had various interpretations, and some variants of this approach have emerged, among which STEAM education stands out. In addition to the four STEM areas, STEAM also includes artistic, humanistic, or social disciplines, which are generically represented by the letter "A". A compelling argument for incorporating these areas is based on the notion that creativity stands out as the most important competency of the 21st century [19], and that the inclusion of the Arts plays a significant role in fostering this skill. Furthermore, it has become more evident that problem solving cannot be limited solely to STEM disciplines. Therefore, STEAM education has presented itself as a more comprehensive and balanced approach to addressing problems and finding solutions [5]. This approach allows the curriculum to extend beyond technical abilities by incorporating creativity and fostering a more profound understanding of cultural and societal contexts which, in turn, cultivates a more comprehensive and enriched learning experience.

According to Quigley and Herro, "the goal of this approach is to prepare students to solve the world's pressing issues through innovation, creativity, critical thinking, effective communication, collaboration, and ultimately new knowledge" [5] (p. 410). As such, STEAM education plays a unique role, as the perspective of the Arts can assist in discovering multiple solutions to problems and provide a form of open knowledge that is rooted in deep subjectivity and divergent thinking, in contrast to scientific objectivity and convergent thinking [20].

Despite its potential, STEAM education has similar shortcomings to STEM education, including the ongoing debate about its definition and the integration of the different areas. This involves addressing questions relating to deciding which types of knowledge and pedagogic practices should be considered, as well as figuring out the most efficient methods to ensure the integration of these disciplines.

Regarding its definition, while Yakman and Lee [21] view STEAM education as "Science and Technology, interpreted through Engineering and the Arts, all based in the language of Mathematics" (p. 1074), other authors perceive STEAM education as an inter- or transdisciplinary approach that is aimed at solving real-world problems [22]. In terms of how the integration of various areas can be achieved, the discussion becomes more complex, because it must ensure the development of diverse competencies as well as knowledge construction. In this regard, Ortiz-Revilla et al. [23] have developed a model for iSTEAM that enables the achievement of such objectives and provides detailed information to understand the process of design, implementation, and evaluation of an iSTEAM didactic sequence. This model proposes an epistemological examination of scientific progress, structured around three levels of scientific commitment: commitment to theories, methods, and aims. Within this triadic framework, the aim is to enhance the development of students' skills, which requires the use of active methodologies (e.g., inquiry and design), is student-centered, and involves collaborative work. Finally, at the level of theories, this commitment is supported by three axes: (i) an epistemological axis, which underscores the significance of viewing the teaching–learning process as an ongoing problem-solving exercise; (ii) a psychological axis, which accentuates the importance of creating a substantial number and variety of situations. This approach offers students the chance to engage with a range of consistent elements, develop and confirm mental frameworks, and achieve a comprehensive understanding or expertise in the conceptual domain that is linked to the subject topics; and (iii) a didactic axis, which emphasizes the effectiveness of the objective–obstacle concept. This concept serves as both a method for choosing the objectives in an educational sequence that is centered on overcoming one or more representations and a tool to regulate didactic interventions, helping to understand what students articulate and execute [23,24].

2.2. PCK

To overcome the challenges faced by teachers in planning and implementing iSTEAM, it is pivotal to support them in the development of pedagogical knowledge and skills by providing opportunities to enhance teachers' PCK.

PCK is a construct that is described by Shulman [25] as one of the domains of teachers' professional knowledge, formed by the intersection of content and pedagogical domains. As such, it encompasses not only a teacher's knowledge but also the transposition of that knowledge into their professional practice [26].

Over the past decades, PCK has emerged as one of the most significant topics in educational research. However, there have been challenges in establishing a consensus on a model for PCK, leading to several proposals (e.g., [27,28]). Consequently, there was a need to consolidate consensus around a standardized proposal for PCK, resulting in the development of the Consensus Model (CM) for PCK, which integrates many ideas from existing PCK models [29]. However, this model has exhibited some weaknesses, such as the ambiguity of its components and the relationship between different forms of PCK [30,31]. The Refined Consensus Model (RCM) emerges as a response to the shortcomings identified in the CM [30]. The RCM delves into the intricate layers of knowledge and experiences that shape teachers' practices, taking into consideration the transformative and integrative features of PCK [32]. This model emphasizes three fundamental domains of PCK: collective PCK (cPCK), personal PCK (pPCK), and enacted PCK (ePCK). Placing ePCK at the core, this model highlights a perspective that is centered on professional practice. Also, the RCM reflects a continuum of grain sizes at which PCK could be considered: discipline-, topic-, and concept-specific levels [30].

According to the RCM, the foundations of PCK constitute the professional knowledge and are represented in the outermost layer, encompassing content knowledge, pedagogical knowledge, knowledge of students, curricular knowledge, and assessment knowledge [30].

The cPCK, represented in the subsequent layer, pertains to the publicly shared PCK among professionals, composed of contributions from teaching experiences, colleagues, and the teachers themselves. The learning context serves as a filter and mediator between cPCK and personal domains (pPCK and ePCK), facilitating a bidirectional exchange of knowledge and skills across the teacher's career. Throughout a teacher's professional life, there is a continual exchange of knowledge among the various components of PCK. Consequently, through processes of filtering and amplification (mediated by the teacher's attitudes and beliefs) of knowledge and skills in each domain, their pPCK is shaped over time [30].

Concerning pPCK, it involves not only explicit and articulable knowledge but also tacit and experiential knowledge that is distinct to each teacher [33]. As for ePCK, it is defined as a manifestation of the decisions that are undertaken during the planning, teaching, and reflection cycle within specific teaching scenarios. The intricacy of capturing this form of PCK is heightened due to its distinctiveness and spontaneous occurrence in classroom contexts [33].

Furthermore, the correlation between ePCK and pPCK is underscored, emphasizing that a more pronounced foundational knowledge can lead to a more prominent manifestation of PCK. Nevertheless, there is a consensus within the PCK research community that a teacher's PCK level is more reliant on the integration and coherence among its components than on the knowledge bases themselves [34]. Additionally, there is a shared understanding that PCK comprises both knowledge and skills, is topic-specific, and is highly individualized and idiosyncratic [31].

2.3. TSPCK

Based on a transformative perspective of PCK (i.e., PCK is considered a new type of knowledge resulting from the act of transforming various types of knowledge), and considering the topic-specific nature of PCK, Mavhunga and Rollnick [35] proposed a model for topic-specific PCK (TSPCK). Subsequently, this model is revisited with reference to the RCM, being then regarded as a grain-size representation (topic-level) of PCK [36].

According to these authors, the model is based on the idea of transforming topic-specific concepts and on the components that facilitate such a transformation, as previously identified by Geddis [37]: (1) students' prior knowledge, (2) curricular relevance, (3) what is difficult to teach, (4) representations including analogies, and (5) pedagogical strategies [35].

Briefly, prior learner knowledge encompasses both common misconceptions and alternative conceptions that are held by students, as well as an accurate understanding of specific content. Curricular saliency, on the other hand, pertains to the significance of learning various topics within the overall curriculum. Within a given topic, it involves discerning the central and peripheral concepts, the requisite prior knowledge, and the sequencing for teaching these concepts. The factor that makes a topic easy or difficult to understand involves the identification of gate-keeping concepts, i.e., those that pose challenges in understanding but may not necessarily be misconceptions. This recognition prompts focused awareness and potential interventions to facilitate their teaching. Representations encompass a diverse array of illustrative tools (examples, illustrations, analogies, simulations, and models) that are pertinent to a given topic. Finally, conceptual teaching strategies refer to effective instructional approaches that are tailored to address learner misconceptions, which are recognized as areas of difficulty, or concepts of particular significance. These strategies utilize combinations of conceptual principles and topic-specific rules as tools to tackle potential confusion and misconceptions. It is important to note that this term does not encompass general pedagogical knowledge strategies [35].

Thus, according to Mavhunga and Rollnick's TSPCK model, a teacher transforms their subject matter knowledge into a version that is suitable for teaching specific learners. This transformation is carried out through reasoning about the content and is mediated by the previously described components [35].

Drawing from the findings of Mavhunga and Rollnick's study [35] involving pre-service teachers and the topic of chemical equilibrium, a reciprocal relationship emerges between PCK and the pedagogical transformation of concepts, and it was previously noted that the latter is an outcome of PCK. In simpler terms, the quality of topic-specific PCK observed in planning and/or teaching is directly connected to how teachers utilize their demonstrated knowledge of the components and their interactions. This utilization, in turn, influences the generation of coherent and comprehensive explanations and responses by teachers [36].

2.4. TPD

Since many educators possess limited knowledge and exhibit low confidence and self-efficacy regarding iSTEAM, it becomes imperative to support teachers in an effective way (e.g., [38–40]).

TPD stands out as the primary mechanism to provide teachers with opportunities to develop their knowledge and pedagogical practices. More specifically, effective TPD allows for the refinement of teachers' content knowledge, pedagogical knowledge, and PCK, and is correlated with heightened motivation, self-reflection, and beliefs, as noted by Baumert and Kunter [41]. Nevertheless, crafting effective iSTEAM-TPD programs is a challenging task, given the numerous barriers that teacher educators must overcome.

TPD can have several typologies but, according to Chai [42], a comprehensive TPD process should encompass three stages: (i) knowledge acquisition, (ii) lesson development and enactment, and (iii) reflective refinement. The same author identifies four increasingly complex forms of TPD: (i) workshop only, (ii) workshops with lesson design, (iii) workshops with lesson design, implementation, and refinement, and (iv) professional learning communities. In the case of a "workshop only," TPD is characterized by being primarily practical, with minimal theoretical components, and typically lasts only a few hours. Regarding "workshops with lesson design," they involve knowledge acquisition, followed by the development of curriculum materials, and extend over days or weeks. A more comprehensive typology of TPD, often lasting at least one week, includes not only the features of workshops and lesson design but also implementation and reflection, often supported through mentoring or coaching. Lastly, Chai also mentions ongoing continuous TPD, which includes, for example, communities of practice [42].

In the literature, some studies have explored TPD in STEAM education, providing support for various benefits that are experienced by participating teachers.

For instance, Romero-Ariza et al. [39] describe the outcomes of an international TPD program in which 102 in-service teachers participated, which included inquiry and socio-scientific issues to promote mathematics and science learning, along with the development of critical thinking and the integration of cultural and fundamental values. According to the pre-test/post-test results, the TPD program had a significant impact on teachers' self-efficacy to implement iSTEM. In another work, Boice et al. [38] performed a study in the context of a year-long STEAM teacher training program with seventeen participants. The results derived from surveys, focus groups, and written reflections are indicative that the TPD program impacted teachers' collaboration, pedagogy, self-efficacy, and arts integration practices.

However, not all TPD initiatives are effective. Among the reasons cited for the ineffectiveness of some TPD initiatives are the short duration of some programs, the lack of follow-up, and the absence of teacher input [43].

3. Materials and Methods

3.1. Participants and Context

This study involved the participation of five Physics teachers (Table 1) who voluntarily took part in a 50-h TPD on iSTEM/iSTEAM. This TPD program entailed the collaborative planning of iSTEM/iSTEAM activities with university members, the implementation of these activities in the classroom, and reflection on the outcomes of the implementation.

Table 1. Teachers' characteristics.

ID	Gender	Age (Years)	Background	Teaching Experience (Years)
AV	F	40	BS Physics and Chemistry Teaching/MSc Chemistry Teaching	15
DC	F	48	BS Physics and Chemistry Teaching	17
JL	M	52	BS Biochemistry	30
TV	F	51	BS Educational Chemistry	29
RF	F	47	BS Physics and Chemistry Teaching/MSc Education	21

This program was carried out within the scope of a project funded by national funds, whose main objective was to understand the effects of STEM activities on students' learning and motivation, as well as their interest in pursuing scientific careers. Overall, approximately 100 teachers participated in this project, and the developed activities focused on various Physics topics for different grade levels (e.g., energy transformations, free fall, pendulum, photovoltaic panels, inclined plane, etc.).

Regarding this study, the participating teachers were those who chose the topic "Electrical circuits with associations in series and parallel". Therefore, during the professional development program, they were more actively involved in the development and implementation of an iSTEAM activity which focused on this topic. Specifically, the TPD program comprised three distinct phases: (a) workshop + lesson design; (b) implementation; and (c) reflection. In the initial phase, teachers participated in workshops that focused on the concept of integrated approaches (iSTEM/iSTEAM) and on the development of the activities to be implemented in the classroom, centered around the chosen topic. During this phase, the teachers were introduced to the background of the module that they would be involved in, and they were given opportunities to provide input into the design of the module. This facilitated the engagement of teachers in inquiry-based activities integrating engineering design. In the second phase of the TPD program, teachers implemented the developed activity in their classrooms with their students. In the third phase (reflection), teachers presented the results of their interventions in a seminar and at a national conference. Also in this phase, a session was conducted for reflection on the work carried out during the TPD program.

3.2. iSTEAM Activity and Curricular Context

The developed activity was focused on the topic "Electrical circuits with associations in series and parallel" and was designed using the concept of reverse engineering, which involves the deconstruction of a product into its components and the analysis of each one to understand how it functions. Additionally, reverse engineering also allows for an understanding of how a particular product was designed and how it can be reproduced or modified. Briefly, the activity began with a short text on reverse engineering, and students were encouraged to take on the role of engineers who had to find out how the new product of a competing company functions to later develop a similar but more innovative product. After that, "Mystery Boxes" were presented to the students. These boxes contained electrical circuits with series and parallel associations of light bulbs. All that students could observe from the exterior were the bulbs and the contact wires that open and close the circuit inside the box. A summary of the main stages of the activity, as well as the curricular contents and learning objectives according to the Portuguese standards, are summarized in Appendix A (Table A1). Considering the guiding documents of the Portuguese curriculum, this activity was aimed at students in the 9th grade.

This activity aligns with the previously described model for iSTEAM [23]: the development of students' competences and knowledge is grounded in the utilization of student-centered pedagogical methodologies, such as inquiry and design. As such, students are required to work collaboratively to solve the presented problem.

Depending on the schools where the teachers taught, i.e., depending on the number of hours per class, this activity was implemented in either three classes of 90 min each or two classes of 135 min. The construction of the final prototype was carried out over additional classes, in science clubs, or at home, depending on the context.

3.3. Research Design

This study followed a pre-test/post-test design with a single group [44], which facilitates the subsequent comparison of participants' reported PCK before and after their involvement in the TPD program.

The reported PCK was examined using a qualitative research methodology following a content analysis approach within an interpretative paradigm. However, in the analysis of the results, a quantitative approach was also employed by transforming variables so that they could be compared based on criteria of degree or intensity.

3.4. Data Collection

Data collection was conducted at distinct moments of the TPD program and using different qualitative instruments to allow for data triangulation. In the initial phase aimed at understanding the level of reported PCK of teachers before the TPD program, an instrument based on CoRe (Content Representation) [45] was employed in the form of a semi-structured interview. During this phase, TPD sessions/workshops were video-recorded, and the content of teachers' interventions was utilized for subsequent analysis. In the final phase (reflection), in addition to a final interview based once again on CoRe, data were also collected regarding teachers' interventions during the reflection session, the regional seminar, and the national conference. Additionally, teachers were asked to provide a written reflection. The data collection instruments are described in the following sections.

3.4.1. CoRe Instrument

The instrument CoRe allows for access to science teachers' PCK about a specific topic, capturing "science teachers' understanding of the content as well as a way of representing this knowledge" [45] (p. 376). According to Kind [46], CoRe is the most useful technique for eliciting and recording teachers' PCK directly.

This instrument consists of two sections. In the first section, teachers are asked to list all the key concepts (Big Ideas) that are associated with a particular topic. In the second section, teachers reply to questions based on the key concepts that they have previously identified: the aim is to reveal teachers' reasoning regarding particular aspects of PCK, such as knowledge of alternative conceptions, ways of testing for understanding, effective sequencing, etc. [45].

Originally presented in the form of a table, this instrument can also be used in the form of interviews, both in groups of teachers or individually [45,47,48]. In this study, we chose to utilize the CoRe as an interview, introducing some modifications to the original instrument to overcome difficulties experienced by teachers, as reported by other authors [49]. The modified questionnaire is presented in Appendix B and was sent to the teachers via email approximately two weeks before the interviews. Thus, CoRe served as the foundation for the semi-structured interview guide. These interviews, conducted individually by the first author with each teacher, were video-recorded and lasted for about one hour each.

3.4.2. Workshop Sessions

During the initial phase of the TPD program and throughout the reflection phase, all sessions conducted with the teachers were recorded on video. This encompassed not only workshop sessions but also the reflection session, the seminar, and the national conference.

Both researchers and other participants in the TPD program were able to pose questions and introduce discussion topics during the sessions. This approach allowed not only for the validation of the responses provided during the interviews using these records but also for the incorporation of additional considerations into the CoRe of each participating teacher.

3.4.3. Written Reflections

At the end of the TPD, teachers were requested to provide a more formal written reflection on the program. To aid them in this process, a guide (Appendix C) was provided approximately one week after the conclusion of the program, serving as a framework for the teachers to elaborate on their final reflections.

3.5. Ethical Issues

All participating teachers volunteered for the research, and assurances were provided regarding participant anonymity and the confidentiality of personal data. Before commencing the study, ethical approval was secured from the Ethics Committee of the Institute of Education from the University of Lisbon. Additionally, teachers were briefed on the research objectives and their nature, and they willingly signed an informed consent agreement, acknowledging their right to withdraw from the study at any point.

3.6. Data Analysis

All interviews and recordings were transcribed by the first author for subsequent analysis. The analysis of the interviews took into consideration the questions from the interview guide based on CoRe and the components of TSPCK [48,50]. Consequently, categories were defined as summarized in Table 2, establishing the correspondence between the interview questions and the components of TSPCK, which form the basis of the content analysis.

Table 2. Correspondence between CoRe questions and TSPCK components [45,50].

CoRe Questions	TSPCK Components
1. What do you intend the students to learn about this concept?	Curricular relevance
2. Why is it important for students to learn about it?	Curricular relevance
3. What content and/or skills students should have as background to properly understand the concept?	Students' prior knowledge
4. What else do you know about this idea (that you do not intend students to know yet)?	Curricular relevance
5. What are the difficulties connected to the teaching and learning of this concept?	What is difficult to teach
6. What is your knowledge about learners' thinking that influences your teaching of these ideas?	Students' prior knowledge
7. Are there any other factors that influence your teaching of these ideas?	--
8. What representations and resources (analogies, metaphors, examples, videos, demonstrations, simulations, practical activities, etc.) are used for students to motivate and be committed to the concept?	Pedagogical strategies
9. What aspects of daily life or other subjects are important in teaching this concept?	Representations
10. What specific ways to you use for ascertaining learners' understanding or confusion around this idea?	Pedagogical strategies

Therefore, after reading the transcriptions, the first author proceeded with their categorization based on the pre-defined categories. The transcriptions of the sessions, seminars, and conference were also analyzed in a similar manner, i.e., using the same categories. The second author also independently codified a subset of the collected data (around 30%) to corroborate interrater reliability. The Cohen's Kappa coefficient between the two researchers was 0.89, suggesting a satisfactory level of agreement between them.

Subsequently, the data analysis involved developing a rubric to score the reported TSPCK of teachers on the topic “Electrical circuits with series and parallel associations”. This rubric was based on the one developed by Mavhunga and Rollnick [35], which, in turn, drew support from pre-existing rubrics [51]. The rubric used in this study was then built upon the five components of TSPCK and adapted to accommodate the data that were related to the topic under study (Table A2, Appendix D). The second author, along with other experts in science education, reviewed the rubrics for content validity.

In addition to this rubric, an expert CoRe was also created (Table A3, Appendix E), which consisted of a CoRe that was collaboratively constructed by the authors (experts in science education) and other collaborators who are knowledgeable in Physics and Science Education, considering the content and learning objectives of the curriculum adopted in Portugal. This CoRe thus constitutes a collective CoRe, considered exemplary in the fundamental concepts of “Electrical circuits with series and parallel associations” and components of the TSPCK. However, it is recognized that there may be other ways to represent this topic to make it suitable for teaching. Thus, this CoRe is not the only possible representation: it is an incomplete and non-absolute generalization but essential to help make the complexity of PCK accessible [52]. In Table A4 (Appendix E), the expert CoRe related to idea 1 (Electric current/Knowing what electric current is) is exemplified.

Based on the rubric and the expert CoRe, the first author primarily analyzed the data, and the second author reviewed them, to reach a consensus on scoring TSPCK for each of its components on a scale from “Limited” to “Exemplary.” An excerpt of an example illustrating how the data for each teacher were analyzed is presented in Table A5 (Appendix F).

4. Results

The analysis of the data collected through the previously described instruments allowed for the assessment of the TSPCK related to the topic in question for each of the teachers before and after their participation in the TPD program. The results of this analysis are presented in Table 3.

Table 3. Scoring of TSPCK components.

TSPCK Components	Ms. AV Pre/Post	Ms. DC Pre/Post	Mr. JL Pre/Post	Ms. TV Pre/Post	Ms. RF Pre/Post
Students’ prior knowledge	2.0/3.5	1.5/2.0	2.0/2.0	1.5/2.5	2.0/2.5
Curricular relevance	1.7/2.6	1.6/3.2	1.4/2.8	1.6/2.8	1.8/3.4
What is difficult to teach	1.5/3.0	2.5/2.5	3.5/4.0	3.0/3.5	1.5/1.5
Representations	3.5/3.5	3.5/4.0	4.0/4.0	3.3/3.8	3.0/3.5
Pedagogical strategies	1.9/3.2	2.0/2.8	3.0/3.6	2.2/2.8	2.6/3.4
AVERAGE	2.1/3.2	2.2/2.9	2.8/3.3	2.3/3.1	2.2/3.1

Based on the results, it is possible to verify that the TSPCK exhibited an improvement across all teachers after participating in the TPD program, as indicated by the average of the considered TSPCK components. In general terms, the lowest increase in the TSPCK (average) was 0.3 (Mr. JL), and the highest increase was 1.1 (Ms. AV). More specifically, the TPD program positively influenced the understanding of students’ required prior knowledge, the recognition of curricular relevance and teaching challenges, and the teaching strategies. Overall, the consistent use of representations remained a strength throughout the evaluation period.

A more comprehensive description of the aspects summarized in Table 3, along with justifications for the given scores, is presented below for each of the teachers.

4.1. Ms. AV

Based on the data collected about Ms. AV, we can observe significant changes in almost all components, and this evolution is reflected in the total TSPCK. As already mentioned, Ms. AV experienced the highest development in TSPCK.

In concrete terms, Ms. AV demonstrated a notable improvement in understanding the needs regarding students' prior knowledge. Prior to TPD, the teacher emphasized two crucial prior knowledge elements for understanding central concepts: the atomic structure and electric current. Ms. AV stressed the importance of knowing about particles that are responsible for electric current and about the movement of charges along single or multiple paths. However, Ms. AV did not mention other relevant prior knowledge, such as simple electrical circuits and components of the circuit. The teacher noted that many students have a sequential reasoning approach regarding electrical circuits: "they think: the current goes in this direction, so if the switch is before the bulb or after the bulb . . . if it is before the lamp, if the switch is open, it does not light up. If it's after, it lights up" (initial interview). After the TPD program, Ms. AV reiterated the importance of knowing about the atomic structure for understanding which particles are responsible for an electric current (final interview). For circuits with series and parallel associations, she highlighted the significance of everyday experiences, such as home installations. Additionally, she mentioned personal characteristics of students, such as curiosity and the ability to manipulate materials. At the end of the TPD program, she highlighted four relevant alternative conceptions, including the indiscriminate use of the term electric current, everyday language issues, the belief that only one wire connects the entire home installation, and the local reasoning about circuits. As Ms. AV mentioned," students look at a circuit at a local level, i.e., giving importance to the place where the pile is, for example, and not considering it as a whole" (final interview).

There was also a significant progression in Ms. AV's perception of curricular relevance. This increase suggests a greater appreciation for the connection between curriculum content and practical application, indicating an improvement in the ability to relate the topics that are covered to students' lives. However, there are opportunities to deepen the approach to associated subideas and the importance attributed to these concepts, as well as to improve the relationships between concepts. Before the TPD program, Ms. AV presented a limited approach in identifying central ideas for teaching the topic of electrical circuits in series and parallel. She outlined three relevant central ideas for teaching the topic (electric current, electrical circuits with associations in series and parallel, and the symbolic representation of components). Associated subideas were not explicitly mentioned, and some connections between central ideas were missing. For example, the professor expected students to learn what a circuit with series and parallel associations is without explicitly stating what she expected them to learn. Additionally, the professor did not highlight curricular aspects, focusing mainly on everyday aspects and the need for a universal language for symbolic representation. However, after the TPD program, there was a notable improvement. Ms. AV identified five relevant central ideas and provided a logical sequence. However, some associated subideas were still missing, despite her mentioning the most important ones. For instance, regarding electric current, Ms. AV expects that her "students learn that it is an ordered movement of electrical charges" (initial interview). The importance attributed to central ideas was still limited, with only the importance of symbolic representation highlighted due to the difficulty in drawing components. Ms. AV made no indication of the relationship between concepts.

Regarding the identification of what is challenging to teach, a substantial change was also verified, indicating a greater awareness of specific areas that may be more complex for students. Thus, prior to the TPD program, Ms. AV did not identify specific concepts as particularly challenging to teach. She considered all concepts, including those related to the discipline, to be challenging due to abstraction, highlighting students' difficulties in mathematical calculations and interpreting statements. As mentioned by Ms. AV in the initial interview, "they have a hard time interpreting when I say "three switches and three light bulbs. Each switch controls only one light bulb". They start right away "Oh teacher, the teacher did not say what it was like. . . whether it was serial or parallel". "Well, no, but you must think". They must interpret and decode what I say" (initial interview). After her participation in the TPD program, Ms. AV acknowledged that many concepts, especially abstract ones, were still challenging. She specified some areas of difficulty, including teaching the real and conventional path of the electric current, assembling parallel electrical circuits, and the symbolic representation of circuits. Regarding this last difficulty, Ms. AV explained that they try to reproduce, even in the schematic representation, what is in the box: "the curved wires, so everything here curved, the batteries, . . . That's exactly what they were seeing. Because they draw exactly what they see" (regional seminar).

Considering the use of representations, Ms. AV maintained a stable score, suggesting consistency in her approach to this component of TSPCK. However, the specificity in describing everyday aspects that were used decreased, indicating a possible area of development in her post-TPD approach. Before the TPD program, Ms. AV employed analogies, such as the river analogy, and videos to illustrate the paths of electric current and its manifestations. However, she acknowledged limitations in the river analogy, which could lead to alternative student conceptions: "maybe they have the notion that it passes once, and the lamp is on. . . I don't know. . . There it is. . . Sometimes when we use this, and that's why it's important to think, we give the comparison to the flow of a river, they may think that the river only passes once in that place" (initial interview). Additionally, she incorporated everyday aspects and topics from other disciplines, such as Christmas lights and Science topics. Following the TPD program, Ms. AV continued to use the river analogy, although she did not specify which representation it supported. Furthermore, she began using models/manipulative materials and a simulator, highlighting the associated concepts. For example, the use of the simulator was important for them "to understand what electric current is because there they actually see a representation" (initial interview). However, there was a reduction in specificity when addressing everyday aspects, with the teacher mentioning them in a more general manner.

Concerning teaching strategies that were employed by Ms. AV, there was also a significant development, especially by incorporating innovative representations and making the lesson more student-centered. However, there is still room for detailing how activities are used to explore students' difficulties and deepen the interrelation between central ideas. Before the TPD program, the teacher used practical activities to expose students' difficulties and conceptions but did not explain how she explored these challenges. Additionally, the elaboration of reports and in-class questions was not detailed regarding the exploration of concepts or their interrelations. Although there were moments for verbal discussion, the lesson was not entirely student-centered, and the explanation of central ideas was limited. In fact, Ms. AV acknowledges that it is a very focused activity. "Students do not have a very active role; they follow the recipe" (initial interview). After the TPD program, Ms. AV continued to use activities to identify student difficulties, emphasizing inquiry-based activities. However, the exploration of these challenges was not explicitly explained. There were implicit moments of verbal discussion, but they were not highlighted by the teacher. While she indicated how some central ideas were explained (forinstance, and regarding circuits with the parallel association, Ms. AV confronted the students: "So, if one light bulb goes out in the bedroom, do all the light bulbs go out? And then, through this, they were able to realize that our facilities are all in parallel" (final interview)), she did not elaborate much on or mention the interrelation between them. However, there was a significant improvement in highlighting the use of representations, such as the simulator, to explore more challenging concepts and make the lesson more student-centered.

4.2. Ms. DC

Overall, Ms. DC showed positive progress across multiple TSPCK components, indicating an overall improvement in her pedagogical knowledge and her ability to address challenges associated with teaching specific content. Noteworthy advancements include an increased recognition of curricular relevance, improved understanding and incorporation of students' prior knowledge, and refinement of teaching strategies.

Before the TPD program, Ms. DC's perception of students' prior knowledge indicated a limited emphasis on incorporating students' existing knowledge into the teaching process. However, post-TPD, there was a slight improvement, suggesting a heightened focus on comprehending and addressing students' prior knowledge to enhance the overall learning experience. More specifically, prior to the TPD program, Ms. DC identified only one essential aspect of prior knowledge for understanding central concepts: the atomic structure (for comprehending the concept of electric current). According to the teacher, knowledge of the atomic structure is essential for students "to understand which particles are responsible for electric current" (initial interview). However, she did not mention other relevant prior knowledge, such as electric current, simple electrical circuits, or components of a circuit. Also, Ms. DC did not reference any pre-existing ideas from the students. Nevertheless, after TPD, the teacher emphasized that understanding electric current is fundamental for students to comprehend electrical circuits with series and parallel associations. However, she did not specify any prior knowledge of other central ideas. Regarding students' prior ideas, Ms. DC only mentioned one relevant alternative conception: the students' belief that there is only one wire connecting the entire household installation.

In terms of curricular relevance, Ms. DC demonstrated a basic acknowledgment of the subject's importance within the curriculum. After the TPD program, a substantial improvement was observed, which indicates an enhanced awareness of the subject's significance and its integration into the broader curriculum. Before the TPD program, Ms. DC identified two central ideas that were relevant to teaching the topic: (a) electrical circuits with components in series and parallel and (b) the symbolic representation of components, with one irrelevant central idea (electric current intensity). However, only one associated subidea was mentioned, namely, that circuits with an association in series are characterized by having only one path for electric current flow, and the mentioned central ideas were not presented with logical sequencing. For instance, the teacher did not refer to relevant central ideas that are important for those that she indicated, and she started by mentioning an irrelevant central idea (electric current intensity) for the topic at hand. Regarding the importance that the teacher attributed to the mentioned central ideas, she did not mention any aspect serving as a foundation for subsequent topics, only stating that students understanding that there is more than one path allows them to comprehend why one bulb lights up and another does not (initial interview). As for the relationship between concepts, no connections were indicated. Following TPD, Ms. DC identified four central ideas that are relevant to teaching the topic (good and bad conductors, components of a circuit, the symbolic representation of circuits, and circuits with series and parallel associations). Considering Ms. DC's responses, not all associated subideas were mentioned, although she referred to the most important ones, such as the composition of materials in the case of good and bad conductors, the function of circuit elements, and the interpretation of symbolic representations. The mentioned central ideas were presented with logical sequencing. Regarding the importance that the teacher attributes to the mentioned central ideas, she generally pointed out some aspects that could serve as a basis for subsequent topics but in a superficial manner. Finally, and regarding the relationship between concepts, Ms. DC established some connections, such as the need for a good conductor in the circuit (wires) for electric current to flow and students knowing and being able to represent circuit components, "so that they can then make and assemble their circuit themselves" (initial interview).

Ms. DC perceived challenges in teaching at a consistent score both before and after the TPD program, suggesting that her outlook on the difficulties that are associated with teaching remained relatively unchanged. Before TPD, Ms. DC mentioned electricity and the direction of the electric current as specific concepts that are challenging to teach. The teacher considered that all these concepts (and others related to the discipline) pose particular difficulty, because they are highly abstract: "This concept is always very difficult to approach (. . .). I think that's how the kids receive it and for the most part they hate it, they know it happens, but it's very strange because you don't see it" (initial interview). After TPD, the teacher still perceived many concepts as particularly challenging due to their abstract nature. However, she specified some aspects related to specific concepts, such as the concept of free electrons and symbolic language. For instance, in Ms. DC's perspective, "the ions, the charge they understand, now maybe the electrons' part makes a little bit of a mess because the electrons are there in the atoms, around the atoms, how do they suddenly start moving there?" (final interview). Moreover, the teacher cited common reasons among students, such as the level of abstraction and issues related to the curriculum.

In the realm of representations, Ms. DC exhibited a consistent dedication to employing diverse and effective representations in the teaching process. Prior to TPD, Ms. DC employed more than two relevant representations. Particularly, she utilized examples, analogies (such as a river for the electric current), and digital resources, and explained how she uses these representations. Nevertheless, she did not fully state which concepts are supported by these representations. Regarding everyday aspects or those from other disciplines, Ms. DC considered the inclusion of various everyday aspects (but not from other subjects), such as Christmas lights, household electrical installations, and safety issues. After engaging in TPD, Ms. DC continued to employ several representations (analogies, simulations, examples, etc.), explained how she uses them, and specified the concepts that they support. For example, and regarding the use of a simulator, the teacher considered that this "was extremely important because we used everything they did or saw in the simulation to be able to draw attention to what we really wanted them to achieve. Thus, they set up circuits with associations in series and in parallel and were still able to see the real and conventional direction of the current" (final interview). Still regarding the use of the simulator, the teacher mentioned that "the students used the simulator and described what they did" (final interview). Once again, Ms. DC mentioned various aspects of daily life, such as Christmas lights, household electrical installations, natural phenomena, and safety issues.

Finally, and regarding teaching strategies, there was a positive shift, reflecting a more developed and effective instructional methodology. Before the TPD program, Ms. DC highlighted the use of activities that allow for the exposure and identification of students' difficulties and conceptions, such as practical activities. However, she did not explicitly explain how she uses these activities to explore students' difficulties, saying only that "I give them the components of the circuits and ask them to start making the connections and usually after 10–15 min, they already understand what the open and closed circuit is" (initial interview). Similarly, the teacher mentioned that students write reports, pose questions in class, and apply knowledge to new situations, but she did not detail how she does this, or which concepts are explored and how they relate. Generally, moments of verbal discussion of difficulties and conceptions were mentioned, and, although practical activities are conducted, they are highly directed, so the lesson is not entirely student-centered. For example, Ms. DC conducts the data registration, not allowing students to do that on their own: "Then I usually build a table on the board where I put the questions that I think are most pertinent: "What did you check?" "So, what if you unscrewed a light bulb?" I do it, and they then point to it" (initial interview). Following TPD, Ms. DC emphasized the use of activities that allow for the exposure and identification of students' difficulties and conceptions, such as inquiry activities, where her intervention "was minimal" (final interview). However, the teacher did not provide detailed explanations of how she uses these activities to explore students' difficulties. There are implicit moments of verbal discussion of difficulties and conceptions, and some were made explicit by the teacher: "I make a list of silly questions and then try them out. . . And that really works" (final interview). Lastly, Ms. DC indicated how some central ideas are explained but did not elaborate much or mention their interrelation. As an example, the teacher mentioned that the circuits with parallel associations were set up by the students while they were doing their explorations, "but they did not notice it. Then, later, I took advantage of the records to talk about it" (final interview).

4.3. Mr. JL

Based on the gathered data about Mr. JL, which is outlined in Table 3, it can be noted that there was notable progress in various TSPCK components. While some aspects, such as understanding students' prior knowledge and a consistent use of representations, remained stable, the professional development program notably influenced his recognition of curricular relevance and identification of challenging topics. Additionally, there was a positive shift in the effectiveness of teaching strategies, showcasing an overall positive impact on Mr. JL's TSPCK. A more detailed description of each component is presented in further detail below.

In terms of understanding students' prior knowledge, Mr. JL maintained a consistent score before and after the TPD program. This suggests that his initial recognition and incorporation of students' existing knowledge into the teaching process remained relatively stable throughout the professional development process. More specifically, before the TPD program, Mr. JL identified two crucial aspects of prior knowledge for understanding central concepts: chemical bonding (specifically ionic and metallic bonding) to comprehend delocalized electrons and ions, which in turn allows for an understanding of the particles with charge and, consequently, the electric current. Furthermore, Mr. JL also mentioned the composition of matter, but did not elaborate about it. Concerning students' prior ideas influencing the teaching of concepts, the teacher only mentioned non-relevant conceptions such as static electricity. In the post-test, i.e., after the TPD program, Mr. JL considered prior knowledge of electric charge, proportionality, and gravitational potential energy to be fundamental. However, only one of these concepts (electric charge) is relevant to the topic at hand. Regarding students' prior ideas, Mr. JL pointed out a pre-existing alternative conception that may influence the teaching of this idea: the meaning of "open" and "closed" in an electrical circuit, which, according to the teacher, "is not immediately clear to students" (initial interview).

Concerning curricular relevance, before the TPD program, Mr. JL made a basic acknowledgment of the subject's importance within the curriculum. However, following TPD, there was a noteworthy advancement, which signifies an enhanced awareness of the subject's significance and its integration into the broader curriculum, reflecting a positive impact from the professional development program. Prior to the TPD program, the teacher mentioned a relevant central idea (electric current), which corresponds to an organized movement of charged particles. Additionally, Mr. JL stated that students are expected to visualize the behavior of this flow along a circuit, without specifying the nature of that behavior. The teacher referred to an irrelevant idea for the topic (potential difference) and mentioned that understanding potential difference facilitates the later analysis of electrical circuits, although he did not attribute significant importance to it, since "students only need a functional concept, which they will later replace with a more elaborate and complex one" (initial interview). Consequently, the importance of these concepts lacks a foundation for subsequent topics, and the relationship between concepts is not specified, nor is the sequence of concepts. Subsequently, after the TPD program, Mr. JL mentioned three relevant central ideas: electric current, the concept of flow (associated with the notion of electric current), and the idea of components in a circuit. Furthermore, Mr. JL indicated a subidea that is associated with the concept of electric current (the notion of ordered movement), and the central ideas were presented in a logical sequence. The teacher, in a very general manner, stated that "the concepts will help students understand what they are doing" (final interview), without specifying. Concerning the concept of flow, the teacher considered it relevant to understanding the concept of electric current. Thus, the teacher provided reasons for the importance of some concepts, and in the case of flow, the reasons for their importance include foundations and specific subsequent topics: for example, in the case of the notion of flow, the professor pointed out that it "should serve as an analogy, as a support to make the connection between what will be a movement of particles with an electric charge, that is, of the electric current" (final interview).

Regarding the identification of challenging topics for teaching, Mr. JL acknowledged the difficulty with a high pre-TPD score. Post-TPD, this recognition intensified, which suggests an increased awareness of the intricacies and challenges that are associated with certain concepts, showcasing a more refined understanding. Specifically, prior to TPD, Mr. JL encountered challenges in explaining electric current to students, as well as the concepts of open and closed circuits, viewing the circuit as a whole, and the limitations of electrical circuit representations. Additionally, the teacher mentioned student conceptions as perpetuating difficulties, like the one related to students having a sequential reasoning approach regarding electrical circuits. As an example, Mr. JL stated the following: "I must explain that while the circuit is open, the ditches are filled with water, and that in an open electric circuit, as it is open, there is no electric current, so they don't think that the electric current has come there and stopped. Many students think that the light bulbs that are closer to the battery should light up" (initial interview). Post-TDP, Mr. JL still faced difficulties in explaining electric current to students, the components of a circuit (the relationship between what students observe and what they assemble), and circuit representations (their limitations). The teacher also mentioned other more general difficulties related to practical work, related to the fact that students do not pay attention to the details (for instance, how many lamps the mystery box had): "for most of my students, it was not very important to be a light bulb or two: the number of light bulbs the box had was not relevant. I was very surprised by that" (final interview).

Both before and after the TPD program, Professor JL demonstrated a strong commitment to the use of representations, maintaining a high score. This consistency indicates that his dedication to employing diverse and effective representations in the teaching process remained unwavering throughout the professional development process. Prior to TPD, Mr. JL identified more than two relevant representations, including the manipulation of materials for assembling electrical circuits and analogies such as the water flow for electric current. Various aspects of everyday life and other disciplines were integrated, allowing students to provide examples as well: "I give a lot of examples, and then they also give the examples they want, and then there are some that fit to the subject and there are others that don't, and we talk about it" (initial interview). Following TPD, Mr. JL continued to use the same representations as before, plus videos and simulations. During the use of these representations, the teacher explained how he uses them and specified which concepts are supported by them: for instance, the analogy with water flow is utilized for the electric current. Finally, the teacher incorporates various aspects of daily life, such as household circuits, the national electrical grid, the composition of transformer elements, high-voltage lines, low-voltage lines, static electricity, lightning, and electric shocks.

In terms of teaching strategies, Mr. JL exhibited a positive shift, reflecting an improvement in his use of teaching strategies and a more refined instructional methodology. Originally, i.e., before TPD, Mr. JL employed diverse and student-centered approaches, such as practical exploration/activities for assembling electrical circuits and to perform measurements. During these activities, the teacher supported students to facilitate their progress: "If I see a group of students who are entertained exploring, I let them be, to see how far they go, and if I see a group of students standing still like that, I get a little closer to them to see if I can give them anything else to move forward" (initial interview). However, even though discussions about students' difficulties and conceptions are evident, the teacher does not anticipate them. The teacher indicated how some concepts (open/closed circuits and electric current) are explained but did not specify the relationship between them. After TPD, the teacher continued to support students to facilitate their progress while fostering their autonomy. The teacher intervenes by posing questions and offering suggestions, like "maybe it's better to start by making a smaller one. . . And then they go back to the starting point, and they start to do little circuits, and as they realize it, they increase the complexity" (final interview). Subsequently, spaces for discussion are created.

During classes, Mr. JL anticipates some of the conceptions, but unpredictable aspects also arise: “and everything and anything comes up, and for us it’s the best possible basis for work. What was foreseen arises and what was unpredictable arises” (final interview). The teacher identified the representations that are used to explain concepts that are identified as difficult. However, the teacher did not specify the interrelation between central ideas.

4.4. Ms. TV

The data collected regarding Ms. TV illustrate significant progress across various TSPCK components. Notable advancements include an improved understanding of students’ prior knowledge, heightened recognition of curricular relevance, and an increased awareness of challenging topics for teaching. The consistent commitment to the use of representations and the positive shift in teaching strategies underscore the overall positive impact on Ms. TV’s TSPCK.

Concerning understanding students’ prior knowledge, Ms. TV demonstrated a notable improvement. This signifies an enhanced focus on recognizing and incorporating students’ existing knowledge into the teaching process, reflecting a positive impact from the TPD program. Prior to TPD, Ms. TV emphasized a foundational prior knowledge for students to grasp the central concepts: the atomic structure. According to the teacher, students struggle to recall even the basic concept of an electron, but Ms. TV did not identify any alternative conceptions. Following the TPD program, Ms. TV identified three important prior knowledge concepts: electrical circuits, electric currents, and the atomic structure. However, once again, there was no mention of alternative conceptions.

In terms of curricular relevance, there was increased awareness of the subject’s significance within the broader curriculum, showcasing a positive development following professional development. Before engaging in the TPD program, Ms. TV identified two central ideas for teaching this topic: electric current and circuits with series and parallel associations. However, the teacher did not specify any subideas associated with these central ideas, and the presentation sequence of ideas lacked logical coherence: as already mentioned, the teacher highlighted electric current as a central idea and mentioned circuits with series and parallel associations as another central idea, omitting some intermediary central ideas, resulting in an illogical sequence of concepts. Regarding the importance of the concepts, the reasons provided by the teacher were not clarified: for instance, Ms. TV claimed that “it is important for students to learn about electrical current to understand how the electrons move along the circuits” (initial interview). Also, the relationship between concepts was roughly indicated, with the teacher mentioning only that “electrical circuits have electric current, which is the movement of charges” (initial interview). Nevertheless, subsequent to the TPD process, Ms. TV identified four relevant central ideas for teaching the topic: (a) components of simple electrical circuits, (b) assembly of simple electrical circuits, (c) electric current, and (d) the symbolic representation of components. However, the teacher associated subideas with only two central ideas (one for each): the subidea of electric current as an organized movement of particles and the difference between circuits with series and parallel associations. As for the sequence of concepts, the teacher placed electrical circuits first when the concept of electric current should come first, which makes the sequence not very logical. For Ms. TV, concepts that are associated with simple electrical circuits were “important for understanding circuits with series and parallel associations” (initial interview). Lastly, the teacher established the relationship between electrical circuits, series and parallel associations, and the functioning of lamps in the following way: “analyzing the circuits, what is the difference between the circuits in terms of circuit assembly and therefore what are the differences between a series association and a parallel association, for example regarding whether the lamps light up or not” (final interview).

Ms. TV’s recognition of challenging topics intensified following TPD, which indicates an enhanced understanding of the intricacies and challenges that are associated with certain concepts. At the beginning of the TPD process, she mentioned the concept of electric current as challenging to teach because “students struggle to grasp the movement of charges" (initial interview). Concerning student conceptions, Ms. TV believed that unfamiliarity with the atomic structure and chemical bonding was limiting, and that the inability to abstract was a determining factor for students' difficulties. After the TPD program, the teacher argued once again that teaching the concept of electric current is challenging, but she also referred to open and closed electrical circuits as challenging: "the question of whether things work up to where the circuit is open, which is related the potential difference, which makes it very difficult for students to understand" (final interview). Regarding student difficulties, the teacher only pointed out common challenges. More specifically, the teacher believed that students' inability to interpret texts limits their development of scientific skills.

Concerning the use of representations, Ms. TV exhibited a consistent commitment, with similar pre- and post-TPD scores. This suggests that her dedication to employing diverse and effective representations in the teaching process remained steadfast throughout the professional development process. More in detail, and prior to TPD, Ms. TV indicated various representations (analogies, simulators, examples, videos, etc.), and for some of them, she explained how she uses them, in addition to the concepts that they support. For instance, the teacher uses the students themselves to explain the concept of the path of the electric current and the routes that it can take. During her classes, Ms. TV incorporates aspects of everyday life, such as domestic electrical installations and Christmas lights. Following TPD, the teacher continued to employ diverse representations such as analogies, simulators, manipulative materials, etc. Again, the teacher specified how she uses some of these representations, as well as the concepts that are supported by them. For example, the teacher uses the analogy of water flow to explain the concept of electric current and traffic to illustrate possible paths for electric charges: "the cars and the traffic jams, they realize that some go this way, others go there, that there are several paths, they realize" (final interview). As examples from daily life, the teacher referred to Christmas lights and domestic electrical installations.

Lastly, and regarding teaching strategies, Ms. TV demonstrated an improvement from the pre-TPD to the post-TPD interview. This positive shift indicates an enhanced use of teaching strategies and a more refined instructional methodology following professional development. Prior to TPD, Ms. TV emphasized the use of activities that allow for the identification of students' difficulties and conceptions, such as practical activities. However, the teacher did not explicitly explain how she uses these activities to explore students' difficulties, although some indications that oral discussions about difficulties and conceptions are used were made: "as they work, I try to see if they are understanding if they are not understanding. So, what if this and that in this circuit. . . And then they can try it" (initial interview). Similarly, the teacher mentioned that students produce reports, ask questions, and apply knowledge to new situations but did not elaborate on how this is done, which concepts are explored, or how they relate. Moreover, Ms. TV identified the representations that are used to explain some concepts, and despite being practical activities, they are highly guided, so the lesson is not entirely student-centered. Following the TPD program, Ms. TV continued to highlight activities exposing students' difficulties and conceptions, such as student-centered inquiry activities. However, once more, she did not explicitly detail how these activities are used to explore students' difficulties. Nonetheless, the teacher provided examples of confronting students' difficulties and conceptions: "So, now imagine that you have three light bulbs, and you want that when you turn on one the others are off. . . And now how would you represent that? So, give me an example of a situation where it would be more beneficial to have a series of components" and see if they understood what they were saying" (final interview). The teacher indicated how some central ideas are explained but did not elaborate much or mention their interrelation. In addition to identifying the representations that are used for explaining general concepts, the teacher highlighted the use of representations, such as simulators, to explore more challenging concepts (e.g., circuits with components in series and parallel).

4.5. Ms. RF

In general, the development of Ms. RF's TSPCK was remarkable in almost all components after her participation in the TPD program. However, the component related to what is challenging to teach remained at a low level. The description of the development of TSPCK in its various components is presented below.

In terms of students' prior knowledge, Ms. RF demonstrated improvement, which indicates an increased focus on recognizing and incorporating students' existing knowledge into the teaching process. More in detail, before her participation in TPD, Ms. RF identified two crucial prior knowledge components for students, the atomic structure and understanding of materials as good or poor conductors, but she did not specify any alternative student conceptions. Following the TPD, the teacher revised her perspective on essential prior knowledge and emphasized the atomic structure for comprehending electric current and the components of an electrical circuit for understanding how it works. Regarding students' preconceived ideas influencing concept teaching, the teacher only mentioned one idea: students' belief in fixed electrons within an atom, which hinders their understanding of metallic bonding, where electrons are free in the metal. According to Ms. RF, "it confuses them to understand what free electrons are in metals and confuses them to realize that everything moves" (final interview).

Regarding the acknowledgment of curricular relevance, there was a substantial advancement following TPD. Before TPD, Ms. RF identified four central ideas as relevant to the topic: a) electrical circuits, b) electric current, c) representation of electrical circuits, and d) series and parallel circuits. However, she only specified one subidea for the symbolic representation of circuits: the ability to represent electrical circuits. Ms. RF makes sure that "students know how to schematize electrical circuits, the symbols, in series and in parallel" (initial interview). The sequence in which the teacher presented central ideas (with electrical circuits mentioned before the concept of electric current) lacked complete logical coherence. Regarding the importance that the teacher attributed to these central ideas, she made no reference to any curricular aspects. For instance, regarding electric current she only affirmed that "it is a natural phenomenon, which we no longer know how to live without" (initial interview). Also, no relationships between concepts were indicated. After the TPD program, the teacher expanded her perspective, identifying seven central ideas for teaching the topic: (a) electricity, (b) electric current, (c) materials as good or poor conductors, (d) simple electrical circuits, (e) the real and conventional direction of electric current, (f) representation of circuits, and (g) circuits with components in series and parallel. However, the teacher only provided some subideas associated with certain central ideas (the oriented movement of electrical charges, open and closed circuits, etc.). Nevertheless, the central ideas were presented in a logically coherent sequence. Regarding the importance that the teacher attributed to these central ideas, she now included foundational aspects and specified subsequent topics. For example, it is important for "students to understand the difference between circuits with series and parallel associations so that they can understand that in one situation the lamps are less bright and that in the other situation the brightness is the same, they have to realize that this is related to the meaning of electric current, which is the fact that there are such carriers of electric charge" (final interview). Additionally, the teacher established relationships between concepts, like in the following case, regarding simple electrical circuits: "they must know that there has to be a source of energy there, a receiver, and that there has to be the conductive material that makes the route and closes the route. This is also essential in series and parallel" (final interview).

Ms. RF consistently obtained a low score in terms of the identification of challenging teaching topics, even after the TPD program, showing limited alteration even after participating in the professional development program. Prior to TPD, the teacher did not identify any concepts as challenging to teach. The difficulties mentioned were attributed to common student challenges, such as the inability to abstract and a lack of autonomy. After TPD, the teacher still did not specify any concepts as difficult to teach. The reasons for the perceived difficulties remained consistent, centering around common student challenges, including difficulties in abstraction and autonomy.

Regarding the utilization of representations, Ms. RF showcased dedication, maintaining high scores before and after the TPD program. This underscores a consistent commitment to incorporating varied and impactful representations in the teaching approach throughout the professional development journey. Specifically, before TPD, the teacher employed various types of representations, including hands-on materials, simulations, and analogies. She explained how she used these representations, namely, the assembly of circuits: "I present them with the materials, and they must assemble a circuit in series and a circuit in parallel. Of course, I had to explain to them what a series circuit was and what a parallel circuit was, giving some examples" (initial interview). However, the teacher did not explicitly state which concepts were supported by each representation, and she only mentioned one real-life aspect. After TPD, the teacher continued to use various types of representations, including hands-on materials, simulations, diagrams, and analogies. She also explained how she utilized these representations and, notably, Ms. RF now explicitly indicated which concepts were supported by each representation. For example, in one of the cases in which the teacher used analogies, the teacher reported the following: "I remember that in a group of good students, the best students, I had to explain, compare the circuit in parallel with the path from the school to the locality where they lived, in which we have alternatives, in which if there was an accident there was another way. And that's how they were able to move forward. Because they were there not knowing how to make the circuit diagram. But after this comparison they were able to move forward" (regional seminar).

Regarding teaching strategies, Ms. RF showed progress, elevating her pre-TPD score. This favorable change signifies an improved application of teaching strategies and a more polished instructional approach in the aftermath of the professional development process. Prior to TPD, the teacher emphasized the use of activities that allowed for the identification of students' difficulties and conceptions, such as practical activities. However, the teacher did not explicitly outline how these activities were employed to explore students' challenges. While the teacher explained how some central ideas were taught, there was no elaboration of their interrelation. Although practical activities were conducted, they were highly directed, leading to a class that was not entirely student-centered: "it is normal to use these more prescriptive activities" (initial interview). After the TPD program, Ms. RF continued to emphasize activities that exposed students' difficulties and conceptions, such as inquiry activities with evident comparisons and verbal discussion of challenges: "I start asking questions that they will have to experiment with and come to conclusions" (final interview). The teacher still explained how some central ideas were taught, but there was limited development and no mention of their interrelation. Importantly, the class became more student-centered: "they had more of a role as a researcher and then I had more of a role of monitoring and helping with the difficulties and then, at the end, taking stock of the results of all the groups and discussing these results with the students" (final interview).

5. Discussion and Conclusions

This study aimed to explore the influence of a TPD program focused in iSTEAM on the PCK related to "Electrical circuits with associations in series and parallel" of five in-service Physics teachers. Through this investigation, we aim to contribute to the increase in existing knowledge on teacher training models in iSTEAM and how they can facilitate the development of PCK. Specifically, this study sought to examine the impact of TPD on the overall PCK of teachers (research question 1) and the effect of TPD on each component of PCK (research question 2).

Furthermore, this study also aims to contribute to exploring pathways for a future definition of a STEAM-PCK. Although this is a secondary aspect of the study, some inferences can be drawn from the results.

Given the absence of any known proposed model for STEAM-PCK, we employed the TSPCK model [35] as our framework. This choice stems from our shared perspective on the transformative nature of PCK and the belief that it is topic-specific, a notion that is highlighted by various authors (e.g., [31]). In fact, some studies confirm that teachers' competencies vary from one subject to another (e.g., [53]). An advantage of adopting the TSPCK model lies in its capacity to provide teachers with specialized tools to address specific challenges that are associated with teaching particular subjects. This involves a deep understanding of how pedagogical strategies can be more effectively adapted to facilitate the comprehension of specific content. Another characteristic of TSPCK is its ability to promote a more personalized and adaptable approach to teaching, allowing teachers to develop specific strategies that cater to the unique needs of their students for a given subject. This results in a more flexible and context-sensitive practice, which is essential in a dynamic educational environment [35,37].

To accomplish our goals, we designed a training program with a focus on diverse aspects such as knowledge acquisition, the active participation of teachers in the development of activities, engagement in discussions about integrated approaches, implementation of activities, and reflection on the entire process.

For organizational reasons, the following discussion will be structured in terms of our research questions.

Regarding RQ1 (What is the effect of TPD on the overall teachers' PCK?), the outcomes discussed in the preceding section suggest that the TPD program had a positive impact on teachers' PCK, albeit with variations observed among individual teachers. As noted by Chai [42], the typology of TPD used in our study (workshop + lesson design + implementation + reflection) stands out as one of the most comprehensive, enabling profound transformations in teachers' PCK. These advantages arise from completing a full development cycle with the guidance of experts. In this study, teachers not only enhanced their knowledge in workshops but, more importantly, applied it in designing lessons and teaching materials collaboratively with experts. During the lesson design phase, the resulting activity was not just a prescribed resource; it emerged from a reflective and shared discussion based on teachers' contexts and experiences. Following this, the activity was implemented in classrooms with small adjustments by each teacher to suit their specific contexts. This hands-on experience allowed teachers to apply vital knowledge, such as understanding their students. In the last phase of the cycle, teachers reflected on the implementation outcomes, identifying what worked well and what could be improved. This reflection was crucial for refining the activity and comparing it with theoretical frameworks that were presented in the workshops, considering both potentials and constraints. As expected, the nature of teacher learning is unpredictable, with some educators undergoing more significant changes than others during professional development [31,54].

Regarding RQ2 (What is the effect of TPD on each PCK component?), the results suggest that the TPD process had positive effects across all components of TSPCK. However, the development of TSPCK components varied among the teachers participating in the TPD program. In general, there was a particular emphasis on the curricular relevance components, followed by the component of what is difficult to teach. These findings are highly significant, because curricular relevance, which involves identifying the essential concepts of a topic, sequencing them, and recognizing their importance, is crucial for the success of the teaching–learning process. According to Loughran and colleagues [55], although big ideas in teaching may align with big ideas in science, they are not automatically interchangeable. This is because the curriculum plays a pivotal role in shaping how teachers perceive and conceptualize these major ideas when instructing on a particular topic. Similarly, knowledge about what is difficult to teach is of paramount importance, since it enables teachers to anticipate and employ pedagogical strategies that help students understand the topic by reorganizing their understanding to eliminate misconceptions [37].

Other findings include the observation that the teachers who participated in this study already possessed a high level of proficiency in using representations, even before the TPD program. Furthermore, despite the positive effect of the TPD program, there are clearly many aspects that need to be considered in terms of TPD effectiveness, since there is still ample room for improvement in almost all components of PCK.

In addition to the research questions, we argue that the findings of this study also contribute to defining a specific PCK for iSTEAM. The existing literature provides suggestions for the definition of STEM-PCK, but these remain somewhat vague and challenging to measure empirically. Saxton and colleagues' proposal [15], grounded in existing research, characterizes STEM-PCK as consisting, firstly, of teachers' knowledge of students' thinking about specific STEM topics, encompassing prior knowledge, common difficulties, and appropriate levels of understanding. Secondly, it addresses the understanding and use of effective strategies to engage students in inquiry processes and facilitate discussions on STEM topics. Finally, it emphasizes the integration of technology to enhance instruction [15]. Building upon Saxton et al.'s perspective, Allen et al. [56] describe STEM-PCK as teachers' knowledge of students' thinking in STEM topics, pedagogical strategies to engage students in inquiry processes, and real-world connections with STEM. An important distinction is that STEM-PCK is viewed as the teacher's knowledge in these areas rather than focusing on the teachers' actions. Hence, a robust STEM-PCK enables teachers to assess conceptual development, inquiry processes, and real-world connections in their students, intentionally adjusting their instruction [56]. Finally, Srikoom et al. [16] proposed that STEM-PCK comprises five components. These include orientations toward teaching STEM, knowledge of STEM curriculum, understanding of students in STEM, instructional strategies and representations for teaching STEM, and knowledge of STEM learning assessment. Each component addresses crucial factors for teachers, such as their views and conceptualizations of STEM education, understanding the role of STEM in curriculum standards and educational materials, establishing STEM concepts as part of student learning outcomes, and assessing student learning through STEM instruction [16].

Thus, considering these proposals, the model for iSTEAM [23], and the results of our study, we envision that STEAM-PCK must include the following aspects: (i) knowledge about what the students know; (ii) knowledge about what the difficult-to-teach topics are; (iii) knowledge about what the curricular relevance of the topic and/or concepts involved is (for each STEAM area); (iv) knowledge about the use of representations; (v) knowledge about the use of active, collaborative, and student-centered teaching strategies; and (vi) knowledge about the integration of subjects through a transdisciplinary approach (or, at least, an interdisciplinary approach). Although many of these aspects were explored in this study with satisfactory results, there is still a long way to go to achieve the ultimate goal of defining a STEAM-PCK, which requires more empirical results.

However, in conclusion, it can be stated that the described TPD process allowed teachers to acquire fundamental competencies to develop and implement STEAM activities on a specific topic. Therefore, the described TPD program contributed to the development of teachers' STEM-PCK on a specific topic, following an approach according to our perspective of integrated STEM education.

The main limitations of this study are related to the number of participants and the consideration of only the reported PCK. Regarding the first limitation, i.e., the number of participants, we argue that although this poses a constraint for generalizing findings, conducting studies with a large number of participants can impact the effectiveness of the learning process and the proximity of the work that is carried out with teachers. Additionally, having a higher number of participants often involves the use of more generalized data collection instruments, such as questionnaires, which are less in-depth and personal, introducing other limitations to the results. In terms of the second limitation (consideration only of reported PCK), we recognize that although this forms the basis for what teachers do in the classroom, it is crucial to assess the extent to which reported PCK aligns with enacted PCK, which constitutes the focus of future work. Additionally, it would be interesting to investigate if the effects of the TPD program are long-lasting through follow-up interviews and classroom observations.

Author Contributions: Conceptualization, I.M. and M.B.; methodology, I.M. and M.B.; software, I.M.; validation, I.M. and M.B.; formal analysis, I.M. and M.B.; investigation, I.M. and M.B.; resources, I.M. and M.B.; data curation, I.M. and M.B.; writing—original draft preparation, I.M.; writing—review and editing, I.M. and M.B.; visualization, I.M. and M.B.; supervision, M.B.; project administration, M.B.; funding acquisition, M.B. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by National Funds through FCT-Portuguese Foundation for Science and Technology, I.P., under the scope of UIDEF—Unidade de Investigação e Desenvolvimento em Educação e Formação, UIDB/04107/2020, https://doi.org/10.54499/UIDB/04107/2020 (accessed on 28 January 2024).

Institutional Review Board Statement: This study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board (or Ethics Committee) of Institute of Education of the University of Lisbon (protocol code 4001, 6 October 2000).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to ethical.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Overview of the activity, curricular contents, and learning objectives according to the guiding documents of the Portuguese curriculum.

Description	Main Curricular Contents	Main Learning Objectives
Students are encouraged to handle the boxes, make predictions, and formulate hypotheses about the components inside them. Students are prompted to record their observations (e.g., whether both lights go out when one bulb is removed, if the intensity increases or decreases, etc.). Students are asked to imagine what could be inside the box, and to draw their ideas.	Science/Physics: Simple electrical circuits Arts: Images as a means of communication	Science/Physics: To know what energy sources are. To understand what energy receivers are. To understand the need for the existence of connecting wires. Arts: To develop skills of appropriation and interpretation in contact with different visual universes. To master the concepts of composition, framing, etc., in different contexts and expressive modalities, such as drawing, for example. Skills: explore, interpretate, formulate hypothesis, draw, record and organize data, etc.
Students are asked to reproduce, using the materials available to them, what is inside each of the boxes, without opening the boxes. After the assemblage of circuits, students can open the box and compare it with what they have built.	Science/Physics: Components of simple electrical circuits. Assemblage of simple electrical circuits. Electrical circuits with lamps in series and in parallel.	Science/Physics: Knowing which components are necessary for building an electrical circuit. Distinguishing between open circuits and closed circuits. Knowing how to identify circuits with series and parallel associations. Knowing how to build circuits with series and parallel associations. Skills: investigating, problem solving, handling materials, making observations, etc.

Table A1. *Cont.*

Description	Main Curricular Contents	Main Learning Objectives
Students are asked to draw the assembly that they created and represent it schematically.	Science/Physics: Symbolic representation of components. Arts: Images as a means of communication.	Science/Physics: Knowing how to represent components symbolically. Being able to identify components from symbols. Knowing how to schematize a circuit. Being able to assemble a circuit from a diagram. Arts: To develop skills of appropriation and interpretation in contact with different visual universes. To perceive, select, and organize data and assign them new meanings. To relate what is known, what is thought, and the different realms of knowledge. Skills: use of multi-representations.
Students are confronted with a cartoon in which two friends discuss the composition of electrical wires. The cartoon ends with one question: copper is a good material to conduct electricity, but are there any others? From this, students must plan and investigate several materials regarding electrical conduction. Students also must take into account several variables, besides electrical conductivity, namely, the cost of the materials and their ductility.	Science/Physics: Good and bad conductors Technology: Computer and other digital devices as tools to support the research and investigation process.	Science/Physics: Knowing what good and bad conductors are. Being able to identify good and bad conductors. Understanding why they are good or bad conductors. Technology: To recognize the potential and main functionalities of tools to support the online research and investigation process. To conduct research using selected and relevant terms in accordance with the theme to be developed. Skills: plan and perform investigations, formulate a hypothesis, record and organize data, explain, draw conclusions, etc.
Students use a PhET simulator to explore the real and conventional direction of an electrical current and explain them. In addition, students can explore several features of the simulator that give them a background for the next curricular contents (not covered by this activity), like the use of measurement instruments.	Science/Physics: Direction of electrical current (real and conventional) Technology: Computers and other digital devices as tools to support the research and investigation process. Mathematics: * Function representation. * Although not included in this activity, the simulator was used to gather some measurement values, which students used to establish mathematical relations between physical quantities (e.g., current intensity, voltage, and resistance)	Science/Physics: To recognize the real and conventional direction of electrical current. Technology: To recognize the potential and main functionalities of tools to support the online research and investigation process. Mathematics: * To represent and interpret a function graphically (including inverse proportionality) and establish the connection between graphical representation and algebraic representation, and vice versa. To develop the ability for abstraction and generalization. Skills: use of muti-representations, observation, explaining, etc.

Table A1. *Cont.*

Description	Main Curricular Contents	Main Learning Objectives
Students apply the acquired knowledge in the previous stages to build an electrical artifact, combining engineering and technology components with creativity.	Science/Physics: All of the above. Technology: Programming concepts. Engineering: Engineering design. Arts: Experimentation and creation.	Science/Physics: Applying the acquired knowledge to build an electrical or electronic (e.g., Arduino, Micro:bit) artifact. Technology: Developing, testing, and validating applications that provide solutions to the stated problem. Engineering: Applying the engineering design process. Arts: Expressing expressiveness in one's work by intentionally selecting concepts, themes, materials, mediums, and techniques. To justify the intentionality of their compositions, using criteria of aesthetic order (lived experiences, experiences, and knowledge). Skills: plan, formulate hypothesis, create, investigate, design an artefact, test, refine, conclude, present the work, etc.

Appendix B

CoRe Interview Protocol:

Introduction

This interview aims to understand how teachers teach and guide their students in learning about the topic "Electrical circuits with series and parallel associations" in a way that is meaningful to them. The information collected will contribute to helping us build activities and/or teaching–learning sequences aimed at the professional development of teachers, according to a STEAM approach.

Part A

Considering your 9th-grade students, what are the central concepts (Big Ideas) about the topic "Electrical circuits with series and parallel associations" that you consider important and fundamental for understanding the topic?

Part B

For each of the concepts you mentioned in the previous question:

1. What do you intend the students to learn about this concept?
2. Why is it important for students to learn about it?
3. What content and/or skills students should have as background to properly understand the concept?
4. What else do you know about this idea (that you do not intend students to know yet)?
5. What are the difficulties connected to the teaching and learning of this concept?
6. What is your knowledge about learners' thinking that influences your teaching of these ideas?
7. Are there any other factors that influence your teaching of these ideas?
8. What representations and resources (analogies, metaphors, examples, videos, demonstrations, simulations, practical activities, etc.) are used for students to motivate and be committed to the concept?
9. What aspects of daily life or other subjects are important in teaching this concept?
10. What specific ways do you use for ascertaining learners' understanding or confusion around this idea?

Appendix C

Introduction

This work involves the elaboration of a reflective text based on the proposed STEAM activity, developed during the TPD. The objective is to assess the extent to which the teacher demonstrates the ability to reflect on the implementation of the STEAM activity in the classroom.

To facilitate your reflection, consider the following dimensions: (1) activity; (2) students; (3) teacher; (4) activity reformulation. For each dimension, take into account the guiding questions, seeking to support your reflection with practical examples.

(1) Activity
- How did you conduct the class using this activity (duration of the activity, students working method, organization of the sequence of classes, modifications to the original activity, etc.)?

(2) Students
- What did the students learn from the activity?
- Which components of the activity helped the students achieve the learning objectives?
- What difficulties did the students encounter? What would you do differently to help students overcome these difficulties?

(3) Teacher
- What challenges did you experience as a teacher in implementing the activity with your students?
- In what ways did your involvement with the activity help you recognize that the use of multiple representations (such as graphs, tables, algebraic expressions) sparks students' interest in their completion and helps them learn?
- How did your involvement with the activity help you recognize that using design engages students in completing it and helps them learn?

(4) Activity reformulation
- How can the activity be improved?

Appendix D

Table A2. Rubric for assessment of reported TSPCK (CoRe) (adapted from [48]).

TSPCK Components/ CoRe Questions	Limited (1)	Basic (2)	Developing (3)	Exemplary (4)
Students' prior knowledge 3. What content and/or skills students should have as background to properly understand the concept? 6. What is your knowledge about learners' thinking that influences your teaching of these ideas?	Does not recognize or identify students' prior knowledge or alternative conceptions.	Identifies one relevant prior knowledge ideas and an alternative conception, along with others that are less relevant.	Identifies two relevant prior knowledge ideas and two alternative conceptions, along with others that are less relevant.	Identifies three or more relevant prior knowledge ideas and three or more alternative conceptions, along with others that are less relevant.

Table A2. *Cont.*

TSPCK Components/ CoRe Questions	Limited (1)	Basic (2)	Developing (3)	Exemplary (4)
Curricular relevance 1. What do you intend the students to learn about this concept? 2. Why is it important for students to learn about it? 4. What else do you know about this idea (that you do not intend students to know yet)?	Identifies irrelevant ideas as central concepts	Identifies two central ideas.	Identifies three relevant central ideas.	Identifies four or more central ideas.
	Does not identify associated subideas.	Identifies an associated subidea.	Identifies several associated subideas.	Identifies all associated subideas.
	Does not indicate the sequence of concepts or indicates a logically unclear sequence of concepts.	Logically unclear sequence of concepts in at least one of the central ideas.	Almost all central ideas are presented in a logical sequence.	Central ideas are presented in a logical sequence.
	Does not indicate the relationship between concepts.	Indicates the relationship between concepts in a rough manner.	The relationship between concepts is evident.	The relationship between concepts is appropriate.
	Does not indicate reasons for the importance of concepts.	The importance of concepts does not encompass the foundation for subsequent topics.	The reasons for the importance of concepts include the foundations but do not specify subsequent topics/ the reasons for the importance of some concepts include the foundations and specify subsequent topics.	The reasons for the importance of concepts include the foundations and specify subsequent topics.
What is difficult to teach? 5. What are the difficulties connected to the teaching and learning of this concept?	Does not identify concepts that are difficult to teach.	Identifies general concepts as being difficult to teach.	Identifies specific and general concepts as difficult.	Identifies specific concepts as difficult.
	Does not specify reasons why concepts are difficult to teach.	Indicates reasons related to common difficulties among students.	Reasons for the difficulties are not specific to central ideas.	Indicates relevant concepts, as well as students' conceptions as perpetuating difficulties.
Representations 8. What representations and resources (analogies, metaphors, examples, videos, demonstrations, simulations, practical activities, etc.) are used for students to motivate and be committed to the concept? 9. What aspects of daily life or other subjects are important in teaching this?	Does not identify any representations.	Identifies a relevant representation.	Identifies two relevant representations.	Identifies more than two relevant representations.
		Does not indicate how the representation is used.	Indicates how the representations are used.	Indicates how the representations are used.
		Does not indicate which concept is supported by the representation.	Indicates which concepts are supported by the representations.	Indicates which concepts are supported by the representations.
		Indicates an aspect of daily life or other subjects.	Indicates two aspects of daily life or other subjects.	Indicates more than two aspects of daily life or other subjects.

Table A2. *Cont.*

TSPCK Components/ CoRe Questions	Limited (1)	Basic (2)	Developing (3)	Exemplary (4)
Pedagogical strategies 8. What representations and resources (analogies, metaphors, examples, videos, demonstrations, simulations, practical activities, etc.) are used for students to motivate and be committed to the concept? 10. What specific ways to you use for ascertaining learners' understanding or confusion around this idea?	Does not mention teaching strategies that allow for exposing/identifying students' difficulties and conceptions.	Evidences the use of activities to expose/identify students' difficulties and conceptions.	Explicitly states the use of activities to expose/identify students' difficulties and conceptions.	Explicitly outlines the use of activities to expose/identify students' difficulties and conceptions and explains how they are used.
	Does not indicate any strategy for confronting and assessing conceptions and difficulties.	Uses verbal discussion of difficulties or conceptions. Indicates how some central ideas will be explained but does not provide their interrelation.	Visible comparisons/confrontations of difficulties and conceptions.	Comparisons/confrontations address conceptions in advance.
	Does not indicate how the central ideas are explored.	Indicates the representations that will be used but does not specify which concepts are supported by them.	Indicates how some central ideas will be explained and their interrelation.	Indicates how all central ideas will be explained and their interrelation.
	Does not indicate an intention to use representations.	Limited involvement of students.	Identifies the representations used to explain general concepts.	Identifies the representations used to explain general concepts and, specifically, those identified as difficult.
	Teacher-centered.		Involvement of students.	Student-centered.

Appendix E

Table A3. Big Ideas (Expert CoRe).

Big Ideas	Subideas
Electric Current (knowing what electric current is)	Knowing which charged particles are responsible for the existence of electric current (electrons and ions). Understanding that electric current results from an organized movement of charged particles. Recognizing that electric current in metals is carried by electrons, while in aqueous solutions, it is carried by ions. Differentiating between the actual direction and conventional direction of the current.
Good and Bad Conductors (knowing what they are and giving examples of good and poor conductors)	Knowing what good and bad conductors are. Being able to identify good and bad conductors. Understanding why they are good or bad conductors.
Elements of a Circuit (knowing and being able to identify the elements of a circuit)	Knowing what energy sources are. Understanding what energy receivers are. Understanding the need for the existence of connecting wires.
Simple Electrical Circuits (understanding what they are and how to assemble simple electrical circuits)	Knowing which components are necessary for building an electrical circuit. Distinguishing between open circuits and closed circuits. Understanding that for the electrical current to flow, the circuit must be closed.

Table A3. *Cont.*

Big Ideas	Subideas
Symbolic Representation of Components (understanding and knowing how to do the symbolic representation of components in an electrical circuit)	Knowing how to represent components symbolically. Being able to identify components from symbols. Knowing how to schematize a circuit. Being able to assemble a circuit from a diagram.
Circuits with Series and Parallel Associations (knowing how to represent and build circuits with series and parallel associations)	Knowing how to identify circuits with series and parallel associations. Knowing how to build circuits with series and parallel associations.

Table A4. Expert CoRe of Idea 1.

CoRe Question	Big Idea 1 Electrical Current
1. What do you intend the students to learn about this concept?	Understand that the electric current is an ordered movement of charged particles (electrons in metals or ions in aqueous solutions). Recognize the difference between the real direction of the current flow (from the negative pole to the positive pole) and the conventional direction (from the positive pole to the negative pole). It is also crucial for students to comprehend the dangers and safety rules related to electric current.
2. Why is it important for students to learn about it?	Understand that there must be a path for this ordered movement, which is ensured by the presence of a generator/source. It is important for them to grasp that there must be free electric charges for an electric current to flow; otherwise, as with bad conductors, there will be no current flow. Regarding the direction of the current, it is crucial for students to understand why there is a conventional direction and its relationship with the nature of science.
3. What content students should have as background to properly understand the concept?	They need to know what particles with electric charge are, that is, they need to recall concepts from the 8th grade, particularly those related to atomic structure (electrons and ions).
4. What else do you know about this idea (that you do not intend students to know yet)?	That for there to be an electric current, there must be a source of energy, where a voltage or potential difference (V) is generated, putting the charged particles into motion. That for the electric current to exist, the electrical circuit must be closed. What is electric current intensity.
5. What are the difficulties connected to the teaching and learning of this concept?	Students have difficulties in visualizing what is not visible. In addition to this, many students struggle with concepts from previous lessons, particularly the structure of the atom and the formation of ions. Many students have difficulty distinguishing the concepts of electric current, energy, potential difference, and power, using these terms interchangeably.
6. What is your knowledge about learners' thinking that influences your teaching of these ideas?	Many students have difficulty distinguishing the concepts of electric current, energy, potential difference, power, etc., using the terms interchangeably. Electric current is created by a flow of positive charges. Electric current is established only in metallic wires. Many students use the terms electricity, electric current, and electrical energy interchangeably.
7. Are there any other factors that influence your teaching of these ideas?	In addition to knowledge of previous content, the ability to abstract and visualize the unseen is crucial. Students can only observe manifestations of the electric current but are unable to see the movement of charged particles.
8. What representations and resources (analogies, metaphors, examples, videos, demonstrations, simulations, practical activities, etc.) are used for students to motivate and be committed to the concept?	Various representations can be employed, including real-life examples illustrating the importance of the electric current, analogies with water flow or crowds, and videos depicting electrical phenomena. Simulators can also be used for students to visualize the real and conventional directions of the current.

Table A4. *Cont.*

CoRe Question	Big Idea 1 Electrical Current
9. What aspects of daily life or other subjects are important in teaching this concept?	All electrical devices/batteries, natural phenomena (thunderstorms), electrical nerve impulses, etc. Exploring why our body is easily penetrated by the electric current.
10. What specific ways to you use for ascertaining learners' understanding or confusion around this idea?	Given its theoretical nature and difficulty for students to comprehend, it is typically assessed by asking for its definition. Through drawings in which they represent the path taken by the current, indicating its conventional direction.

Appendix F

Table A5. Excerpt of the scoring of Ms. AV's interview after TPD (post-test).

TSPCK Component	Score	Score Justification/Evidence
Students' prior knowl-edge	Average = 3.5 * * The average score was calculated based on the partial scores for the following criteria: Identifies two relevant students' prior knowledge and two alternative conceptions, along with others that are less relevant. Partial score: Developing (3) Identifies three or more alternative conceptions, along with others that are less relevant. Partial score: Exemplary (4)	3- What content and/or skills students should have as background to properly understand the concept? "Electrical current (. . .) atomic structure to understand which charged particles are responsible for electric current." (final interview) "Electrical circuits with series and parallel associations What is previous for them. . . to understand, in a house, okay, one bulb turns off, and the others go out. The Christmas tree lights. . . and it's important to have this knowledge, that some of them have, even if they're not aware they have it, then when we talk, they become aware that they have it." (final interview) In addition to previous knowledge, the teacher also mentions that the personal characteristics of the students are decisive, i.e., "some are more comfortable, curious, to manipulate the box, that's innate, it's the natural contraption. Some are even afraid to remove the bulb and break it." (final interview) 6- What is your knowledge about learners' thinking that influences your teaching of these ideas? Electrical current "For example, electric current (quantity) and then the concept of electric current. Therefore, the quantity electric current with the definition of electric current." (final interview) Simple electrical circuits "Everyday language issues. . . turning on the light, turning off the light. . . sometimes they think it's the opposite. . . I don't know if it's because of the switch, the turning off, the turning on, there's something there that really. . . because an open circuit doesn't light up, maybe that's it." (final interview) "The idea that students tend to look at a circuit locally, i.e., giving importance to the location of the battery, for example, and not considering it as a whole. How they think. . . if there's an opening there in the electrical circuits, then if it's there, they think everything can still light up by going through another path. . ." (final interview) Electrical circuits with series and parallel associations "(. . .) they think it's a single wire that connects the various rooms in the house, and therefore, all the light bulbs, all the appliances." (regional seminar) COMMENT: According to the teacher, knowledge of atomic structure is essential for understanding which particles are responsible for the electric current. Regarding useful prior knowledge for understanding circuits with series and parallel associations, the teacher emphasizes the importance of everyday experiences, such as domestic installations. In addition to prior knowledge, the teacher also notes that students' personal characteristics, such as curiosity and ease in manipulating materials, are crucial. However, the teacher does not mention any prior knowledge for many of the central ideas. [Developing (3)] Regarding students' prior ideas, the teacher mentions four relevant alternative conceptions: students may think and use the term "electric current" interchangeably (as a quantity measuring the flow of charge and as the ordered movement of particles with charge), issues of everyday language (turning on and off the light/switch), the issue of local reasoning when students consider a circuit without considering it as a whole, and finally, the fact that students may think that there is only one wire connecting the entire home installation. [Exemplary (4)]

References

1. Hsu, Y.S.; Fang, S.C. Opportunities and Challenges of STEM Education. In *Asia-Pacific STEM Teaching Practices*; Hsu, Y., Yeh, Y., Eds.; Springer Nature: Singapore, 2019; pp. 1–16. [CrossRef]
2. Sanders, M. STEM, STEM Education, STEMmania. *Technol. Teach.* **2009**, *68*, 20–26.
3. Mejias, S.; Thompson, N.; Sedas, R.M.; Rosin, M.; Soep, E.; Peppler, K.; Roche, J.; Wong, J.; Hurley, M.; Bell, P.; et al. The trouble with STEAM and Why We Use It Anyway. *Sci. Educ.* **2021**, *105*, 209–231. [CrossRef]
4. Aguilera, D.; Ortiz-Revilla, J. STEM vs. STEAM Education and Student Creativity: A Systematic Literature Review. *Educ. Sci.* **2021**, *11*, 331. [CrossRef]
5. Quigley, C.F.; Herro, D. "Finding the Joy in the Unknown:" Implementation of STEAM Teaching Practices in Middle School Science and Math Classrooms. *J. Sci. Educ. Technol.* **2016**, *25*, 410–426. [CrossRef]
6. Caton, J.C. Don't Run Out Of STEAM! Barriers to a Transdisciplinary Learning Approach. *J. STEM Teach. Educ.* **2021**, *56*, 4. [CrossRef]
7. Burrows, A.; Slater, T. A proposed integrated STEM framework for contemporary teacher preparation. *Teach. Educ. Pract.* **2015**, *28*, 318–330.
8. Honey, M.; Pearson, G.; Schweingruber, A. *STEM Integration in K-12 Education: Status, Prospects, and an Agenda for Research*; National Academies Press: Washington, DC, USA, 2014.
9. Margot, K.C.; Kettler, T. Teachers' perception of STEM integration and education: A systematic literature review. *Int. J. STEM Educ.* **2019**, *6*, 1–16. [CrossRef]
10. Ring, E.A.; Dare, E.A.; Crotty, E.A.; Roehrig, G.H. The evolution of teacher conceptions of STEM education throughout an intensive professional development experience. *J. Sci. Teach. Educ.* **2017**, *28*, 444–467. [CrossRef]
11. Roehring, G.H.; Moore, T.J.; Wang, H.H.; Park, M.S. Is Adding the E Enough? Investigating the Impact of K-12 Engineering Standards on the Implementation of STEM Integration. *Sch. Sci. Math.* **2012**, *112*, 31–44. [CrossRef]
12. Kim, D.; Bolger, M. Analysis of Korean Elementary Pre-Service Teachers' Changing Attitudes about Integrated STEAM Pedagogy through Developing Lesson Plans. *Int. J. Sci. Math. Educ.* **2017**, *15*, 587–605. [CrossRef]
13. Wong, J.T.; Bui, N.N.; Fields, D.T.; Hughes, B.S. A Learning Experience Design Approach to Online Professional Development for Teaching Science through the Arts: Evaluation of Teacher Content Knowledge, Self-Efficacy and STEAM Perceptions. *J. Sci. Teach. Educ.* **2022**, *34*, 593–623. [CrossRef]
14. Li, Y.; Wang, K.; Xiao, Y.; Froyd, J.E. Research and Trends in STEM Education: A Systematic Review of Journal Publications. *Int. J. STEM Educ.* **2020**, *7*, 11. [CrossRef]
15. Saxton, E.; Burns, R.; Holveck, S.; Kelley, S.; Prince, D.; Rigelman, N.; Skinner, E.A. A Common Measurement System for K-12 STEM education: Adopting an educational evaluation methodology that elevates theoretical foundations and systems thinking. *Stud. Educ. Eval.* **2014**, *40*, 18–35. [CrossRef]
16. Srikoom, W.; Faikhamta, C.; Hanuscin, D. Dimensions of Effective STEM Integrated Teaching Practice. *K-12 STEM Educ.* **2018**, *4*, 313–330.
17. Crippen, K.J.; Antonenko, P.D. Designing for Collaborative Problem Solving in STEM Cyberlearning. In *Cognition, Metacognition, and Culture in STEM Education*; Dori, Y., Mevarech, Z., Baker, D., Eds.; Springer: Cham, Switzerland, 2018; Volume 24, pp. 89–116. [CrossRef]
18. Toma, R.B.; Greca, I.M. The Effect of Integrative STEM Instruction on Elementary Students' Attitudes toward Science. *EURASIA J. Math. Sci. Tech. Ed.* **2018**, *14*, 1383–1395. [CrossRef] [PubMed]
19. Trilling, B.; Fadel, C. *21st Century Skills: Learning for Life in Our Times*; Jossey-Bass: San Francisco, CA, USA, 2009.
20. Sanz-Camarero, R.; Ortiz-Revilla, J.; Greca, I.M. The Impact of Integrated STEAM Education on Arts Education: A Systematic Review. *Educ. Sci.* **2023**, *13*, 1139. [CrossRef]
21. Yakman, G.; Lee, H. Exploring the exemplary STEAM education in the US as a practical educational framework for Korea. *J. Korean Assoc. Sci. Educ.* **2012**, *32*, 1072–1086. [CrossRef]
22. Lin, C.-L.; Tsai, C.-Y. The effect of a pedagogical STEAM model on students' project competence and learning motivation. *J. Sci. Educ. Tech.* **2021**, *30*, 112–124. [CrossRef]
23. Ortiz-Revilla, J.; Greca, I.M.; Meneses-Villagrá, J.A. Effects of an integrated STEAM approach on the development of competence in primary education students (Efectos de una propuesta STEAM integrada en el desarrollo competencial del alumnado de Educación Primaria). *J. Stud. Educ. Dev.* **2021**, *44*, 838–870. [CrossRef]
24. Ortiz-Revilla, J.; Adúriz-Bravo, A.; Greca, I.M. A Framework for Epistemological Discussion on Integrated STEM Education. *Sci. Educ.* **2020**, *29*, 857–880. [CrossRef]
25. Shulman, L.S. Those Who Understand: Knowledge Growth in Teaching. *Educ. Res.* **1986**, *15*, 4–14. [CrossRef]
26. Baxter, J.A.; Lederman, N.G. Assessment and Measurement of Pedagogical Content Knowledge. In *Examining Pedagogical Content Knowledge*; Gess-Newsome, J., Lederman, N.G., Eds.; Springer: Dordrecht, The Netherlands, 1999; Volume 6, pp. 147–161. [CrossRef]
27. Grossman, P. *The Making of a Teacher*, 2nd ed.; Teachers College Press: New York, NY, USA, 1990.
28. Magnusson, S.; Krajcik, J.; Borko, H. Nature, sources, and development of pedagogical content knowledge for science teaching. In *Examining Pedagogical Content Knowledge*; Gess-Newsome, J., Lederman, N.G., Eds.; Springer: Dordrecht, The Netherlands, 1999; Volume 6, pp. 95–132. [CrossRef]

29. Gess-Newsome, J. A Model of Teacher Professional Knowledge and Skill Including PCK. In *Re-Examining Pedagogical Content Knowledge in Science Education*, 1st ed.; Berry, A., Friedrichsen, P., Loughran, J., Eds.; Routledge: New York, NY, USA, 2015; pp. 28–42. [CrossRef]
30. Carlson, J.; Daehler, K.R. The Refined Consensus Model of Pedagogical Content Knowledge in Science Education. In *Repositioning Pedagogical Content Knowledge in Teachers' Knowledge for Teaching Science*; Hume, A., Cooper, R., Borowski, A., Eds.; Springer Nature: Singapore, 2019; pp. 77–92. [CrossRef]
31. Chan, K.K.H.; Hume, A. Towards a Consensus Model: Literature Review of How Science Teachers' Pedagogical Content Knowledge Is Investigated in Empirical Studies. In *Repositioning Pedagogical Content Knowledge in Teachers' Knowledge for Teaching Science*; Hume, A., Cooper, R., Borowski, A., Eds.; Springer Nature: Singapore, 2019; pp. 3–76. [CrossRef]
32. Gess-Newsome, J. Pedagogical Content Knowledge: An Introduction and Orientation. In *Examining Pedagogical Content Knowledge*; Gess-Newsome, J., Lederman, N.G., Eds.; Springer: Dordrecht, The Netherlands, 1999; Volume 6, pp. 3–17. [CrossRef]
33. Alonzo, A.C.; Berry, A.; Nilsson, P. Unpacking the Complexity of Science Teachers' PCK in Action: Enacted and Personal PCK. In *Repositioning Pedagogical Content Knowledge in Teachers' Knowledge for Teaching Science*; Hume, A., Cooper, R., Borowski, A., Eds.; Springer Nature: Singapore, 2019; pp. 273–288. [CrossRef]
34. Park, S.; Suh, J.K. The PCK Map Approach to Capturing the Complexity of Enacted PCK (ePCK) and Pedagogical Reasoning in Science Teaching. In *Repositioning Pedagogical Content Knowledge in Teachers' Knowledge for Teaching Science*; Hume, A., Cooper, R., Borowski, A., Eds.; Springer Nature: Singapore, 2019; pp. 187–199. [CrossRef]
35. Mavhunga, E.; Rollnick, M. Improving PCK of Chemical Equilibrium in Pre-service Teachers. *Afr. J. Res. Math.* **2013**, *17*, 113–125. [CrossRef]
36. Mavhunga, E. Exposing Pathways for Developing Teacher Pedagogical Content Knowledge at the Topic Level in Science. In *Repositioning Pedagogical Content Knowledge in Teachers' Knowledge for Teaching Science*; Hume, A., Cooper, R., Borowski, A., Eds.; Springer Nature: Singapore, 2019; pp. 131–150. [CrossRef]
37. Geddis, A.N. Transforming subject-matter knowledge: The role of pedagogical content knowledge in learning to reflect on teaching. *Int. J. Sci. Educ.* **1993**, *15*, 673–683. [CrossRef]
38. Boice, K.L.; Jackson, J.R.; Alemdar, M.; Rao, A.E.; Grossman, S.; Usselman, M. Supporting Teachers on Their STEAM Journey: A Collaborative STEAM Teacher Training Program. *Educ. Sci.* **2021**, *11*, 105. [CrossRef]
39. Romero-Ariza, M.; Quesada, A.; Abril, A.M.; Cobo, C. Changing teachers' self-efficacy, beliefs and practices through STEAM teacher professional development (Cambios en la autoeficacia, creencias y prácticas docentes en la formación STEAM de profesorado). *J. Stud. Educ. Dev.* **2021**, *44*, 942–969. [CrossRef]
40. Nadelson, L.S.; Callahan, J.; Pyke, P.; Hay, A.; Dance, M.; Pfiester, J. Teacher STEM Perception and Preparation: Inquiry-Based STEM Professional Development for Elementary Teachers. *J. Educ. Res.* **2013**, *106*, 157–168. [CrossRef]
41. Baumert, J.; Kunter, M. The COACTIV Model of Teachers' Professional Competence. In *Cognitive Activation in the Mathematics Classroom and Professional Competence of Teachers*; Kunter, M., Baumert, J., Blum, W., Klusmann, U., Krauss, S., Neubrand, M., Eds.; Springer: Boston, MA, USA, 2013; Volume 8, pp. 25–48. [CrossRef]
42. Chai, C.S. Teacher professional development for science, technology, engineering and mathematics (STEM) education: A review from the perspectives of technological pedagogical content (TPACK). *Asia-Pac. Edu. Res.* **2019**, *28*, 5–13. [CrossRef]
43. Darling-Hammond, L.; Hyler, M.E.; Gardner, M. *Effective Teacher Professional Development*; Learning Policy Institute: Palo Alto, CA, USA, 2017.
44. Creswell, J.W. *Educational Research. Planning, Conducting, and Evaluating Quantitative and Qualitative Research*, 4th ed.; Pearson Education: London, UK, 2002.
45. Loughran, J.J.; Mulhall, P.; Berry, A. In search of pedagogical content knowledge in science: Developing ways of articulating and documenting professional practice. *J. Res. Sci. Teach.* **2004**, *41*, 370–391. [CrossRef]
46. Kind, V. Pedagogical content knowledge in science education: Perspectives and potential for progress. *Stud. Sci. Educ.* **2009**, *45*, 169–204. [CrossRef]
47. Lehane, L.; Bertram, A. Getting to the CoRe of it: A review of a specific PCK conceptual lens in science educational research. *Educ. Quim.* **2016**, *27*, 52–58. [CrossRef]
48. Mazibe, E.N.; Coetzee, C.; Gaigher, E. A Comparison Between Reported and Enacted Pedagogical Content Knowledge (PCK) About Graphs of Motion. *Res. Sci. Educ.* **2020**, *50*, 941–964. [CrossRef]
49. Alvarado, C.; Canada, F.; Garritz, A.; Mellado, V. Canonical pedagogical content knowledge by CoRes for teaching acid–base chemistry at high school. *Chem. Educ. Res. Pract.* **2015**, *16*, 603–618. [CrossRef]
50. Mazibe, E.N. Teaching Graphs of Motion: Translating Pedagogical Content Knowledge into Practice. Master's Dissertation, University of Pretoria, Pretoria, South Africa, 2017.
51. Park, S.; Jang, J.Y.; Chen, Y.C.; Jung, J. Is Pedagogical Content Knowledge (PCK) Necessary for Reformed Science Teaching?: Evidence from an Empirical Study. *Res. Sci. Educ.* **2011**, *41*, 245–260. [CrossRef]
52. Loughran, J.J. Understanding and valuing the development of pedagogical content knowledge in science teacher education. In *Towards Research-Based Science Teacher Education. Proceedings of the 18th Symposium on Chemical and Science Education*; Eilks, I., Ralle, B., Eds.; Shaker Verlag: Aachen, Germany, 2006; pp. 65–76.
53. Aydin, S.; Friedrichsen, P.M.; Boz, Y.; Hanuscin, D.L. Examination of the topic-specific nature of pedagogical content knowledge in teaching electrochemical cells and nuclear reactions. *Chem. Educ. Res. Pract.* **2014**, *15*, 658–674. [CrossRef]

54. Borko, H. Professional Development and Teacher Learning: Mapping the Terrain. *Educ. Res.* **2004**, *33*, 3–15. [CrossRef]
55. Loughran, J.; Berry, A.; Mulhall, P. *Understanding and Developing Science Teachers' Pedagogical Content Knowledge*, 2nd ed.; Loughran, J., Berry, A., Mulhall, P., Eds.; Sense Publishers: Rotterdam, The Netherlands, 2006.
56. Allen, M.; Webb, A.W.; Matthews, C.E. Adaptive Teaching in STEM: Characteristics for Effectiveness. *Theory Pract.* **2016**, *55*, 217–224. [CrossRef]