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Teaching Biology Lessons Using Digital Technology: A Contextualized Mixed-Methods Study on Pre-Service Biology Teachers' Enacted TPACK

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Abstract: Pre-service biology teachers must apply Technological Pedagogical and Content Knowledge (TPACK) acquired at university in real classroom situations to utilize the instructional potential of digital technologies for teaching biology. So far, there is little evidence on how pre-service biology teachers translate TPACK into teaching practice. The present study addresses this gap by accompanying 42 pre-service biology teachers in planning, implementing, and reflecting on a biology lesson as part of their internship semester at school. Data were collected via written lesson plans, videotaped lesson observations, and stimulated-recall reflection interviews and evaluated by applying a sequential explanatory mixed-method design. The results indicate that pre-service biology teachers enact their TPACK by focusing on technology with the content of the subject receding into the background. In addition, pre-service biology teachers focus particularly on aspects that serve to structure the lesson, rather than on aspects of student activation. The use of emerging technologies in the classroom seems to lead to insecurity among pre-service biology teachers for various reasons, whereby surface characteristics and structuring lesson aspects are focused. Within the sample, we can distinguish between two types of TPACK enactment: the split-focus type separates between content and technology, whereas the novelty-focus type systematically links content and technology, utilizing the technology as a tool for subject teaching.

Keywords: TPACK; science teaching; teaching with ICT; teacher professional development; classroom teaching

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1. Introduction

Teaching scientific content requires visualizing invisible or abstract and complex concepts [1,2]. Utilizing digital technology such as animations or simulations can contribute to overcoming this challenge [2,3]. In addition, digital technologies initiate higher-quality learning processes by shifting the students' learning activity from passive to interactive [4]. Combining extended representational opportunities with student-oriented and interactive learning enables the development of advanced learning scenarios [5] and implies the relinquishment of control by encouraging student collaboration and exploration [6]. However, teachers widely use digital technology (in science teaching) for presentation purposes [5,7–10].

One reason for the limited deployment of digital technology is the lack of digitalization-related competencies among teachers [11,12] and difficulties in identifying instructionally meaningful technology implementation [13]. These skills must be developed within teacher education [14], for example by utilizing authentic hands-on experiences with digital technology in the classroom [15]. In Germany, pre-service teachers have limited opportunities to experiment with digital technology during their school internships. This limits their ability to develop technology-related skills, which is why teacher educators recommend systematic integration into the internship [16]. This systematic integration of digital skills into teacher education requires conceptualization within a framework such as the Technological Pedagogical and Content Knowledge framework (TPACK; [17]), which is widely used internationally [18].

1.1. TPACK Framework and TPACK Measurement

The TPACK framework conceptualizes the knowledge a teacher needs to successfully use (digital) technology for teaching subject content in seven domains. Technological Knowledge (TK), Pedagogical Knowledge (PK), and Content Knowledge (CK) form the basic domains. Intersections of the basic domains lead to the blended domains of Technological Pedagogical Knowledge (TPK), Technological Content Knowledge (TCK), and Pedagogical Content Knowledge (PCK). The seventh domain, Technological Pedagogical And Content Knowledge (TPACK), represents the interface of all knowledge domains [17].

In TPACK research, two different theoretical perspectives on the epistemological nature of the construct have emerged: the integrative view and the transformative view. According to the integrative view, the framework is composed entirely and exclusively of its subdomains and their intersections in the TPACK Venn diagram or, in practical terms, their interplay in teaching [1,19]. In this regard, growth in TK implies the growth of TPACK as a whole. According to the transformative view, TPACK is developed from its subdomains but constitutes a distinct and unique knowledge domain [1,19]. Empirical results demonstrating an indirect influence of the basic domains on TPACK via the blended domains support the transformative perspective [20–23].

Results could be more consistent concerning the concrete interplay of the blended knowledge domains. While Pamuk et al. [21] identified all blended domains influencing TPACK, other studies found that only a combination of selected blended domains such as TPK and TCK [20,24], PCK and TPK [22], or PCK and TCK [25] influenced TPACK. One possible reason for these inconsistent results could lie in the respective studies' contextual conditions [22], such as the emergence of the selected digital technology or the focus of the intervention [26]. Another key contextual factor represents pre-service teachers' attitudes, influencing how the pre-service teachers experience individual methods for TPACK development [27].

The integrative and transformative views on TPACK presuppose different methodological approaches in measuring the construct [1]. Most TPACK self-assessments measure TPACK on its subdomains [28], corresponding to an integrative TPACK construct. In contrast, performance assessments predominantly collect TPACK as an overall construct [29], corresponding to the transformative TPACK perspective.

To date, the majority of what we know about TPACK is based on self-reports [30,31]. However, self-reports do not necessarily correspond to the results of more objective assessment methods, such as knowledge tests [32] or enacted TPACK measures [23,33,34]. There are indications that the pre-service teachers' ability for self-assessment decreases with increasing task complexity (e.g., with increasing reference to teaching practice) [35]. Additionally, there remains a gap between TPACK acquired at the university and enacted TPACK in practice [15].

1.2. Enacted TPACK

In the past decade, different models of TPACK enactment have emerged, such as TPACK-in-action [36], TPACK-Practical [2], TPACK-in-practice [37], and TPACK-in-situ [38]. These models differ in their domain-specific focus and their degree of concretization. For example, some models focus on selected data sources (didactic designs; [38]) or TPACK domains (blended TK domains; [37]).

In the following, the term enacted TPACK addresses the practical application of TPACK as a knowledge domain. In this context, enacted TPACK is defined as a dynamic, highly contextual [2,39], and content-centered [37] construct developed by and guiding lesson planning, implementation, and reflection [2,31]. This definition aligns with expertise research and teacher professionalization models, describing a gradual development of competence through practical experience such as reflective lesson planning and implementation [40–42].

Through continuous practical experience over time and influenced by beliefs, values, as well as affective dispositions, novices develop their declarative knowledge acquired at university into routinized procedural teaching scripts, enabling spontaneous reactions in complex and dynamic classroom situations [42].

Studies examining TPACK as enacted in the classroom while considering contextual factors are relatively rare [31,43–45]. More knowledge is needed to understand how TPACK is implemented in real classrooms [46,47]. From a methodological perspective, studies in this field rely mainly on rubrics, scarcely considering contextual factors. Moreover, they are often based on a single data source [29]. These assessment instruments usually focus on the (blended) TK domains (TK, TPK, TCK, and TPACK) while overlooking the PCK domain [48]. Consequently, it is recommended to combine different data sets to comprehensively assess enacted TPACK by comparing teachers' decision-making processes with their ability to implement plans [49]. This is particularly important because the enactment of TPACK represents a complex and dynamic process involving bidirectional relationships between theory and practice [9].

Table 1 provides an overview of the current state of research on the enactment of TPACK in classroom practice.

Table 1. Overview of the sample and data sets of the enacted TPACK references used. Abbreviations: S = Science Subject/U = Undefined Subject/PST = Pre-Service Teachers/IST = In-Service Teachers/LP = Lesson Planning/LI = Lesson Implementation/LR = Lesson Reflection.

Reference	Sample				Data Sets		
	Size	S/U	PST	IST	LP	LI	LR
Aktaş and Özmen (2020) [50]	6	S	X		X	X	X
Akyuz (2023) [43]	4	S	X		X	X	X
Aumann and Weitzel (2023) [51]	3	S	X		X	X	X
DeCoito and Richardson (2018) [7]	17	U		X			X
Janssen et al. (2019) [52]	73	U	X		X		
Kapici and Akcay (2023) [53]	38	S	X		X		
Nielsen et al. (2015) [54]	2	S		X	X	X	X
Ocak and Baran (2019) [55]	4	S		X	X	X	X
Pringle et al. (2015) [8]	525	S		X	X		
Stinken-Rösner et al. (2023) [48]	31	S	X		X		
Szeto and Cheng (2017) [9]	23	U		X	X	X	
Valtonen et al. (2020) [56]	86	U	X		X		
Walan (2020) [45]	2	S		X		X	X
von Kotzebue (2022) [23]	82	S	X		X		
Yeh et al. (2015) [57]	7	S	X		X	X	

The ability of pre-service teachers to integrate TPACK into their teaching practice varies widely [57]. Some feel anxious about using digital technology in the classroom [53] due to limited resources or a lack of readiness to use digital technology [7].

While teachers often describe how they use digital technology in terms of TK or TPK [7], they struggle to understand how to effectively use it to teach subject content [7,52,53,56]. The perceived usefulness of digital technology in teaching may predict how well pre-service teachers integrate TPACK into their teaching practice [23].

Since teaching using digital technology implies challenges in classroom management and guiding students [45,55], it seems reasonable that implementing technology-enriched lessons will lead to growth in these areas [50], as well as to conflicts between student learning and classroom management [54]. There is evidence that pre-service teachers with low technology-related self-efficacy or low TPACK enactment are predominantly concerned with practical matters regarding the use of digital technology, such as classroom and time management, leading to less consideration of the blended PK domains or content-related aspects [43,51]. One reason could be that unfamiliarity with digital technology preoccupies the pre-service teachers' concentration capacity [43,51–53].

As a result, pre-service teachers, as well as experienced and innovative in-service teachers, use digital technology predominantly in a teacher-centered way [54,55] with low levels of student autonomy [23]. Accordingly, presentation software represents one of the most commonly used technologies in the classroom [7–9].

Moreover, pre-service teachers conduct the selection of subject contents in technology-enriched lessons based on familiarity or easiness [56], and reduce the content-related cognitive demand to a low level, such as the reproduction of information [8,23]. However, results are inconsistent concerning PCK. While in Akyuz' [43] study, PCK represented one of the overall lowest enacted knowledge domains in pre-service teachers' TPACK enactment, in Ocak and Baran's [55] study, PCK represented the central reference domain for in-service teachers' technology selection and decisions. The different contextual factors of the studies mentioned may have caused inconsistencies in the data. These include sample characteristics and the intervention or the selected digital technology [56]. Based on the research conducted by Valtonen et al. [56], it seems that PK has a significant impact on the development of TPACK. It is viewed as both a challenging area and an area of confidence that encourages pre-service teachers to think critically. Stinken-Rösner et al. [48] suggest incorporating PCK-focused TPACK interventions in existing science programs to address PCK aspects by utilizing the potential of digital technology. One way to do this is by providing digital technology enabling inquiry-based learning [8,45,50]. This approach can help pre-service teachers gain experience using digital technology effectively, facilitating a transition to more student-centered scenarios [50].

1.3. Scope of the Study

We require further evidence to understand how TPACK can be applied in actual teaching practices. The data provide an incoherent and partly contradictory picture of TPACK enactment. Demonstrating good enacted TPACK in terms of lesson planning does not guarantee corresponding results in lesson implementation, as pre-service teachers partly underestimate technology preparation and misjudge the technology-related skills of students [57]. Furthermore, it is crucial to consider contextual factors thoroughly. However, existing studies have some limitations in this regard. Firstly, many studies do not include contextual factors in their assessment instruments [29]. Secondly, some studies only focus on selected phases of teaching, such as lesson planning or implementation [7,8,23,48,52,53,56]. Lastly, some studies represent case studies that rely on very small samples [43,50,51,54,55]. Even when data sets from different teaching phases such as lesson planning and implementation are examined, they are only occasionally related.

To understand the complex process of TPACK enactment in lesson planning, implementation, and reflection, a more comprehensive measurement [9,48], using larger samples [55], is required. The present study addresses the need for research on enacted TPACK by examining pre-service biology teachers' technology-infused lesson plans, implementations, and reflections in authentic classroom situations in a subject- and technology-specific manner. The objective is to identify patterns in the enactment of TPACK in a particular context. Our research question is as follows:

RQ: To what extent do pre-service biology teachers apply their TPACK acquired at university in authentic lesson planning, implementation, and reflection?

2. Materials and Methods

This study adopts the transformative perspective on TPACK development [1]. This perspective makes the following assumptions: (1) TPK, PCK, and TCK directly influence TPACK. (2) TPACK is a distinct body of knowledge conceptually differing from the mere combination of the blended domains.

Therefore, and based on the defined contextual conditions of the present study, we focus on the blended PK domains (TPK and PCK) and TPACK as a distinct knowledge domain. Since (enacted) TPACK represents a fuzzy construct, a detailed description of the sample, context, data structure, instruments, and data analysis process becomes mandatory.

2.1. Sample

The sample of this study consists of 42 pre-service biology teachers (11 (26.19%) = male; 31 (73.81%) = female) in their internship semester. An internship semester occurs during the second semester of a master's degree. According to the module handbook of the study program, the pre-service biology teachers had attended subject didactic courses to the extent of nine credits. During their studies, the pre-service biology teachers discussed media instruction topics but did not refer to the use of digital technology in teaching biology. We conducted the study over three consecutive semesters, and all pre-service biology teachers participated with informed consent. Of the total 61 pre-service biology teachers, 42 agreed to participate in data collection.

2.2. Research Design and Context

During the course of the 14-week internship semester, the pre-service biology teachers were accompanied to gain insights into their technology-enhanced classroom teaching. In this context, they were mentored by in-service teachers who determined the lesson content that the pre-service teachers had to teach. Since the assignment of pre-service teachers to internship classes and mentors is the responsibility of the respective internship school, it was not possible to ensure consistent class levels or lesson contents in this study. Accordingly, the lessons covered a wide range of topics, from human biology and cell biology to ecology, genetics, and evolution.

To ensure instructional consistency, the study focused on the use of student-generated explainer videos as a specific use of digital technology. Student-generated explainer videos represent a novel learning experience for the pre-service biology teachers [58].

The pre-service biology teachers were provided with a workshop to equip themselves with the necessary TPACK for the use of digital technology. We developed the workshop using Tondeur's et al. [15,59] SQD model [60]. The workshop followed the flipped classroom concept and consisted of one session (90 min), including preparation and a follow-up task. Its structure and duration ensured ecological validity. The workshop content was developed in line with the measurement instrument (see Section 2.4) to confirm that the intervention and evaluation were aligned.

Initially, pre-service biology teachers compiled the necessary TPACK online during self-study. The learning materials comprised information on the quality criteria for student-generated explainer videos in the biology classroom, provided as interactive explainer videos, textual summaries, audio sessions, and links to more in-depth sources of information. Next, the pre-service biology teachers took part in an on-site workshop of 90 min, in which they discussed the content of the online course and analyzed exemplary lesson plan outlines. Furthermore, a range of technological options regarding hardware and software were introduced, compared, and discussed during the workshop. The pre-service biology teachers then made a justified decision in favor of one technological option, formed small groups, and created a short explainer video on a given biological subject content using the selected technology. Subsequently, they were asked to briefly reflect on their selected hardware and software relating to the implementation in their internship classes.

Following the workshop, the pre-service biology teachers planned, implemented, and reflected on a lesson of 90 min at their internship schools. In these lessons, their students created explainer videos regarding a biological subject content. The pre-service biology teachers were allowed to freely select hardware and software and borrow equipment from the university if there was a need for more reliable access to technology at the internship school. Figure 1 depicts the research design of the study. It relates the individual aspects of the TPACK workshop at university to the TPACK enactment at the internship school in terms of their chronological sequence (x-axis) and their alignment to practice (y-axis).

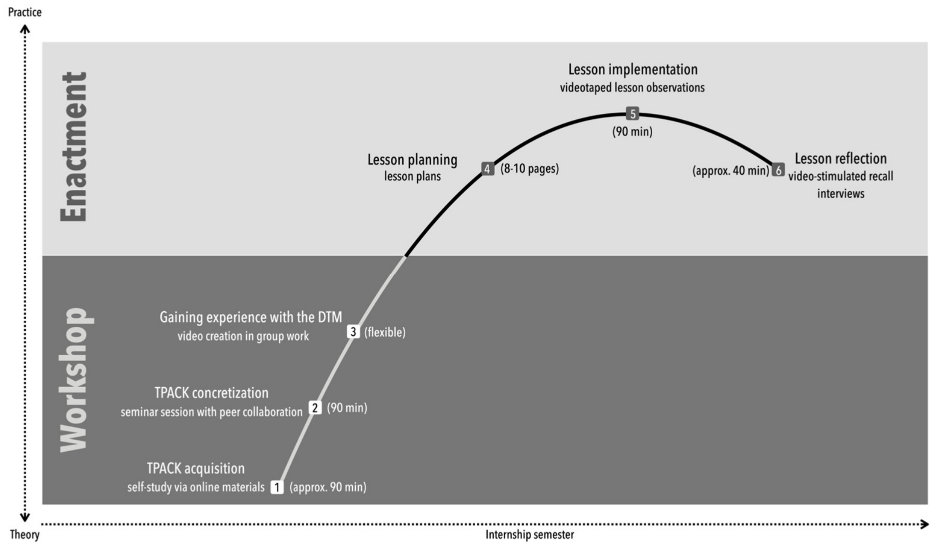

Figure 1. The research design of the study.

2.3. Data Collection Procedure

We collected the following data via the pre-service biology teachers: (1) lesson plans, (2) lesson implementation, and (3) lesson reflection. More details about the data sets are explained below:

(1) Lesson Plans The lesson plans consisted of around 8–10 pages. They included subject analysis, instructional and methodological planning, lesson outlines, and materials. The instructional planning laid out and justified instructional considerations, while the methodological planning explained the specific procedure for the lesson in causal terms.
(2) Videotaped Lesson Observations During lesson implementation (90 min), one of the researchers accompanied and videotaped the lesson on-site. The researcher also took field notes during the visits. As the study focused solely on the pre-service biology teachers, the camera was positioned so that only the pre-service biology teachers (the desk and the blackboard) were visible. As the lesson was particularly interactive, a wireless microphone enabled audio recordings of the teacher at all times.
(3) Semi-Structured Stimulated Recall Interviews Immediately after lesson implementation, the researcher conducted semi-structured stimulated recall reflection interviews with the pre-service biology teachers. In this procedure, the researcher and the pre-service biology teachers viewed 3–4 sequences of the videotaped lesson observations based on a conversation guideline and used them as reflection stimuli. The selected sequences are related to certain aspects of the lesson (e.g., the feedback phase). This approach provided the pre-service biology teachers with a defined focus of reflection and encouraged them to reflect upon instruction-related and student-centered topics beyond aspects of classroom management [61]. Additionally, the approach allowed the pre-service biology teachers to address the issues that concerned them the most [56]. The interviews lasted around 40 min on average and were transcribed.

2.4. Research Instrument

In 2023, we developed a rubric to analyze how pre-service science teachers enacted TPACK based on lesson planning, implementation, and reflection (EnTPACK rubric) [29]. Thus, the rubric allows us to compare TPACK enactment across these different data sets and identify discontinuities between them. In line with the preceding TPACK workshop (see Section 2.1), the rubric was specified regarding TK, PK, and CK (student-generated explainer videos in the science classroom).

The development of the instrument and the corresponding definition of the TPACK domains followed a contextualized, theory-guided, and literature-based approach. In this approach, theoretical models (subcategories) were selected according to the application context and assigned to the TPACK domains (categories). In a further step, observable indicators from empirical studies were identified using a literature review and, in turn, assigned to the subcategories. As a result, the TPACK domains were defined on the basis of empirical data regarding the quality criteria of student-generated explainer videos in science teaching.

According to the application context, the transformative view of TPACK, and empirical data on TPACK enactment, the EnTPACK rubric comprises the blended PK domains (PCK and TPK) and the distinct TPACK domain. These domains form the categories of the rubric [29]. To enable an independent measurement of these categories, they were defined distinctly. In other words, indicators in the TPACK category are in no direct relation to indicators within the TPK or PCK category. Appendix A provides an overview of the categories, subcategories, criteria, and indicators of the EnTPACK rubric.

Thus, the rubric represents a particular and contextualized instrument for assessing how pre-service science teachers enact their TPACK in terms of lesson planning, implementation, and reflection. Construct validity of the rubric was ensured through the literature-based development process [62]. Subsequently, expert judgments were collected to assure content validity. In addition, inter-rater reliability was assessed by two independent raters, resulting in a good overall reliability of the instrument (Intraclass correlation coefficient (ICC) = 0.873).

Table 2 presents an exemplary insight into applying the EnTPACK rubric to pre-service teachers' lesson plans. In this example, one of the pre-service biology teachers defines central aspects of content in the lesson plan that are essential for achieving the content-related lesson objective (Indicator: PCK cs2-c). These are further distinguished from the secondary aspects of the content (Indicator: PCK cs2-c). Accordingly, the indicators PCK cs2-a and PCK cs2-c can be assigned to this lesson plan excerpt. Both of these indicators are located in the second criterion of the content structuring subcategory within the PCK category.

Table 2. Example of applying the EnTPACK rubric to a lesson plan excerpt.

"The identification of all organs involved as well as the two hormones adrenaline and noradrenaline, which trigger biological stress reactions, is elementary for the application of special strategies of stress management. [. . .] The HPA axis and glucocorticoid functions are not part of the required expertise for this topic" (Lesson Plan RA25NR).	
Indicator	(PCK cs2-a) The pre-service teacher (PST) emphasizes key aspects of content (e.g., emphasizes their importance). (PCK cs2-c) The PST distinguishes the key aspects from non-essential aspects.
Criterion	(PCK cs2) The PST focuses specifically on central key aspects of the subject content.
Subcategory	(PCK cs) Content structuring
Category	PCK

2.5. Data Analysis and Evaluation

In the first step of the data analysis, the three data sets (lesson plans, videotaped lesson observations, and transcribed reflection interviews) were deductively coded using the observable indicators of the EnTPACK rubric. Subsequently, the criteria were rated on a four-point Likert scale (0–3) depending on the quantity of coded indicators. The subcategories were then rated based on the criteria means, and the categories were rated based on the subcategory means.

As a result, the data were available in both numerical and textual form. This allowed the combination of quantitative and qualitative evaluation methods using a sequential explanatory mixed-methods design [63]. In this approach, qualitative methods are applied to explain quantitatively identified patterns. Specifically, in the present study, numerical data regarding lesson planning and implementation enabled insights into patterns of pre-service biology teachers' teaching, whereas textual data regarding lesson planning and reflection provided pedagogical reasonings.

The numerical data were examined in increasing depth for patterns. This involved first focusing on the categories, then the subcategories, and finally the coded indicators. We first analyzed the lesson planning and implementation data exploratively at the category level (TPACK, PCK, and TPK) to gain an overview of the TPACK domains in the data sets. Mean values and standard deviations were calculated, using IBM SPSS (version 29.0.0.0), and compared within the categories to analyze the extent to which the TPACK domains were implemented in lesson planning and implementation. The same procedure was then applied at the subcategory level. In addition, subcategories were merged into higher-level variables of teaching quality (student activation and lesson structuring) using transformation via SPSS. After examining the higher-level variables for normal distribution, we calculated differences in central tendencies by applying the non-parametric Wilcoxon signed-rank test.

In order to gain a deeper insight into the decisive differences between and within the data sets, we then analyzed the data sets for discontinuities at the indicator level. To identify discontinuities between lesson planning, implementation, and reflection, we compared the data sets (lesson plans, videotaped lesson observation, and semi-structured stimulated recall interviews) at the level of the coded indicators. For this purpose, we compared the occurrence of individual indicators to other indicators and between lesson planning, implementation, and reflection. To visualize these patterns more clearly, we used heatmaps of the indicators, which were colored in grayscale according to the number of total occurrences among the sample (white = 0; black = 42) within the data sets. This provided us with detailed information about which concrete aspects differ between pre-service biology teachers' planning, implementation, and reflection of technology-enhanced biology teaching.

Next, the observed patterns were examined qualitatively using the lesson planning and reflection data. For this purpose, cases assigned to quantitatively observed patterns were analyzed via a comparative thematic analysis [63] using VERBI MAXQDA 2020 (version 20.4.1). In this process, the data sets of the respective cases were coded inductively to identify similarities, differences, and co-occurrences within and between the pattern groups. This qualitative deepening provided the basis for an interpretation of the observed patterns.

3. Results

We present the study results in two parts. First, we provide the arithmetic mean values of the lesson planning and lesson implementation data sets on category, subcategory, and indicator levels to identify patterns and discontinuities. Second, we deepen the results qualitatively using lesson planning and lesson reflection data.

3.1. Category Level: TPACK, PCK, and TPK

Table 3 shows the arithmetic mean values of the categories regarding the lesson planning and implementation of pre-service biology teachers. There is a high level of variation within the TPACK domain in lesson planning and implementation. TPACK and TPK exhibit higher values than PCK, which remains below the scale average (1.50) across both data sets. In lesson implementation, the TPACK domain records the highest mean value. In the transition from lesson planning to implementation, PCK decreases while TPACK and TPK increase.

Results from the Wilcoxon signed-rank test (see Table 4) show that in lesson planning, there is a significant difference in the central tendencies between TPK and PCK, as well as between TPK and TPACK, at an alpha level of 0.05. In lesson implementation, significant differences in central tendency were observed between PCK and TPACK and between PCK and TPK.

Table 3. Arithmetic mean values at category level (TPACK, PCK, and TPK) in terms of lesson planning (LP) and lesson implementation (LI) on a Likert scale from 0 to 3. (For detailed indicator descriptions, see Appendix A).

	TPACK (LP)	TPACK (LI)	PCK (LP)	PCK (LI)	TPK (LP)	TPK (LI)
Mean	1.42	1.88	1.27	1.18	1.77	1.85
Standard Deviation	0.66	0.62	0.43	0.43	0.46	0.41

Table 4. Wilcoxon signed-rank test results of the TPACK domains regarding lesson planning (LP) and lesson implementation (LI). (For detailed indicator descriptions, see Appendix A).

	PCK (LP) and TPACK (LP)	PCK (LP) and TPK (LP)	TPK (LP) and TPACK (LP)	PCK (LI) and TPACK (LI)	PCK (LI) and TPK (LI)	TPK (LI) and TPACK (LI)
Z	−9.70	−5.07	−2.50	−4.72	−5.55	−0.11
Asymptotic Significance (Two-Sided)	0.33	<0.001	0.012	<0.001	<0.001	0.91

3.2. Subcategory Level: Lesson Structuring and Student Activation

Table 5 shows the results of descriptive statistics at the subcategory level of the En-TPACK rubric. The statistics reveal a high value of dispersion, especially in the TPACK subcategories and the TPK subcategory of time management. In this regard, the PCK subcategory cognitive activation and the TPK subcategory scaffolding cognitive load show the lowest standard deviation (below 0.60) in both lesson planning and lesson implementation.

Table 5. Arithmetic mean values at subcategory level in terms of lesson planning (LP) and lesson implementation (LI) on a Likert scale from 0 to 3. Abbreviations: TPACK alo = alignment of the use of digital technology with lesson objectives/TPACK asc = alignment of the use of digital technology with subject content/TPK il = interactive learning/PCK ca = cognitive activation/PCK cs = content structuring/TPK tm = time management/TPK scl = scaffolding cognitive load. (For detailed indicator formulations, see Appendix A).

	TPACK				Student Activation				Lesson Structuring					
	TPACK alo (LP)	TPACK alo (LI)	TPACK asc (LP)	TPACK asc (LI)	TPK il (LP)	TPK il (LI)	PCK ca (LP)	PCK ca (LI)	PCK cs (LP)	PCK cs (LI)	TPK tm (LP)	TPK tm (LI)	TPK scl (LP)	TPK scl (LI)
Mean	2.00	1.69	0.83	2.07	1.10	1.12	1.07	0.89	1.46	1.46	2.62	2.40	1.59	2.04
Standard Deviation	0.80	0.72	0.88	0.89	0.76	0.71	0.42	0.33	0.72	0.70	0.73	0.89	0.53	0.38

Subcategories related to lesson structuring record higher mean values than subcategories related to student activation. To test the difference between student activation and lesson structuring for significance, the student activation subcategories (PCK cognitive activation, and TPK interactive learning), as well as the lesson structure subcategories (PCK content structuring, TPK scaffolding cognitive load, and TPK time management), were each transformed into one variable within the data sets of lesson planning and lesson implementation. Wilcoxon signed-rank test results show significant differences between student activation and lesson structuring in lesson planning and implementation (see Table 6).

Table 6. Wilcoxon signed-rank test results of student activation and lesson structuring regarding lesson planning (LP) and lesson implementation (LI).

	Student Activation (LP) and Lesson Structuring (LP)	**Student Activation (LI) and Lesson Structuring (LI)**
Z	−4.91	−5.62
Asymptotic Significance (Two-Sided)	<0.001	<0.001

3.3. Indicator Level: Discontinuities between the Data Sets

The following section presents selected indicators exhibiting noticeable discontinuities between the data sets of lesson planning, implementation, and reflection. Within the TPACK domain, the alignment between the use of digital technology and the subject content is discrepant among the data sets. Table 7 depicts selected indicators of the subcategory explicitly dealing with the characteristics defining the subject content as particularly suitable for the use of digital technology. The pre-service biology teachers addressed these indicators in lesson implementation but frequently omitted them in lesson planning or lesson reflection.

Table 7. Discontinuities within the data sets in the TPACK subcategory of alignment between digital technology and subject content. Abbreviations: TPACK asc-a = Selected subject content is self-contained/TPACK asc-b = Selected subject content is limited in scope/TPACK asc-c = Selected subject content is complex/TPACK asc-d = Selected subject content is dynamic (for detailed indicator formulations, see Appendix A). Cells indicate the number of pre-service biology teachers for which the respective indicator (columns) was coded within the respective data set (rows).

	TPACK asc-a	**TPACK asc-b**	**TPACK asc-c**	**TPACK asc-d**
LP	1	13	12	3
LI	33	39	24	27
LR	3	7	6	12
= 0–5	= 6–10	= 11–15	= 16–20	= 21–25
= 26–30	= 31–35	= 36–40	= 41–45	

Within the PCK subcategory cognitive activation, the pre-service biology teachers predominantly thematize the relevance of the subject content in the students' lives during lesson planning. In contrast, this aspect is seldom addressed in lesson implementation or reflection (see Table 8).

Table 8. Discontinuities within the data sets in the *PCK* subcategory of cognitive activation. Abbreviations: PCK ca2-a = The relevance of the subject content is discussed/PCK ca2-b = A relevant question or problem constitutes the basis of the video creation/PCK ca2-c = A context (e.g., phenomenon) is provided (for detailed indicator formulations, see Appendix A). Cells indicate the number of pre-service biology teachers for which the respective indicator (columns) was coded within the respective data set (rows).

	PCK ca2-a	**PCK ca2-b**	**PCK ca2-c**	
LP	23	5	10	
LI	5	5	9	
LR	5	2	5	
= 0–5	= 6–10	= 11–15	= 16–20	= 21–25
= 26–30	= 31–35	= 36–40	= 41–45	

Table 9 presents the TPK subcategory scaffolding cognitive load divided into three criteria: supporting students on demand (1) in using hardware and software, (2) in video planning, and (3) in self-organizing group work. The pre-service biology teachers offered demand-oriented support as a "guide by the side" among all three criteria to a greater extent in lesson implementation than was mentioned in lesson planning and reflection. In lesson planning and reflection, most attention is paid to the demand-oriented support of students regarding hardware and software usage, while supporting students in self-organized group work is considered to a lesser extent.

Table 9. Discontinuities within the data sets in the *TPK* subcategory of scaffolding cognitive load. Abbreviations: TPK scl1-d = Support for handling the digital technology/TPK scl2-d = Support for video planning and design/TPK scl3-c = Support for self-organized group work (For detailed indicator formulations, see Appendix A). Cells indicate the number of pre-service biology teachers for which the respective indicator (columns) was coded within the respective data set (rows).

	TPK scl1-d	**TPK scl2-d**	**TPK scl3-c**	
LP	22	14	6	
LI	32	41	33	
LR	9	10	1	
= 0–5	= 6–10	= 11–15	= 16–20	= 21–25
= 26–30	= 31–35	= 36–40	= 41–45	

3.4. Qualitative Deepening

The qualitative data from lesson planning and reflection are analyzed in depth to better understand the underlying reasons for the results presented in the previous sections. Initially, we summarize the quantitatively identified types, patterns, and discontinuities in TPACK enactment.

Although high TPK and low PCK values remain relatively constant across the sample and data sets, TPACK represents a highly variable domain (Section 3.2). Therefore, cases were merged into two types: pre-service biology teachers with (1) high TPK but low blended CK domains (PCK and TPACK), and (2) high blended TK domains (TPK and TPACK) but low PCK.

Additionally, an overarching pattern was identified between the level of student activation and lesson structure between lesson planning and implementation. Furthermore, discontinuities were found between the data sets among all domains (PCK, TPK, and TPACK) (Section 3.3).

Cases were selected for qualitative deepening if they fulfilled the type, pattern, or discrepancy criteria. For example, cases were selected for type (1) if they recorded comparatively high TPK but low PCK and TPACK values. Appendix B depicts the values for the relevant variables of all cases (n = 42) as a heatmap. The variables were arranged according to the identified patterns to enable comparison. In addition, the cells were colored according to the corresponding value to ensure more intuitive readability. We classified the cases into low (red: 0–0.99), middle (yellow: 1–1.99), and high (green: 2–3) performer based on their values on the Likert scale. Appendix B is intended to provide transparency with regard to the distribution of cases on the individual variables. This aims to increase the traceability and reproducibility of the present qualitative results.

The following sections discuss the characteristics of the identified types (Sections 3.4.1 and 3.4.2), commonalities of those types (Section 3.4.3), overarching patterns (Section 3.4.4), and discontinuities (Section 3.4.5) based on pre-service biology teachers' lesson planning and reflection. We provide a citation at the beginning of each section to explain its respective characteristics.

3.4.1. Type 1: High TPK but Low Blended CK Domains

Cases assigned to this type are characterized by (1) a separation between content and the use of digital technology, (2) perceived overwhelming demands with the use of technology, and (3) a focus on surface characteristics of the lesson.

(1) Separation between Digital Technology and Content

> "*Because it [the use of technology] is simply added on or in between, I didn't know where to focus and what the priority in the classroom should be. Is it more the work with digital media in general or is the content at least as important.*"
>
> (LR KE04JG).

Several pre-service biology teachers regard digital technology as an autonomous learning content to be taught independently of the subject content. Moreover, they rate the learning objectives regarding the use of technology as equal to or even more important than the content-related learning objectives. For example, they state the use of tablets as their primary learning objective, address explainer videos as a separate form of content, and prioritize the design quality of the explainer videos. In some lesson plans, the focus is explicitly not on the subject content "but on the use of digital media" (LP WE30VJ), which is why pre-service biology teachers reduce content deliberately to provide capacity for technologically complex tasks. In this context, it is sometimes more critical to the pre-service biology teachers "that they [the students] develop media skills, [and] that they use the tablet accordingly" (LR TE09SM).

(2) Pre-Service Biology Teachers Overload with Technology Use

> "*I didn't get to grips with shooting this video and all that. I was also initially overwhelmed by the whole task.*"
>
> (LR LI13VB).

Pre-service biology teachers often describe themselves as worried about or overwhelmed by using digital technology in the classroom. They usually explain their self-perception with low confidence in the use of digital technology, describing themselves as "not a technology person" (LR SA27LK), "not a technology freak" (LR KE04JG), or articulating "too much respect for [. . .] working with the iPads" (LR ÜB02SB). In addition, they report some difficulties in estimating the technology-related skills of the students, a lack of guidance in the form of literature or curricular guidelines, and insufficient preparation.

(3) Focus on the Surface Characteristics of the Lesson

> "*That is why it was important to me that everything runs smoothly, that when I want to use the laptop, it works straight away or is already switched on so that it doesn't have to boot first. It was important to me that I could create a smooth transition because I know that if it's not working, it will lead to disruption, and at the same time, the teacher will also get nervous. It's a vicious circle.*"
>
> (LR TE09SM).

Overall, the perceived overload due to the use of technology encourages the pre-service biology teachers to prioritize undisturbed teaching before students' content-related learning. Concerns about time management lead to omitting relevant PCK aspects, such as feedback in favor of the students' technological preparation. Some pre-service biology teachers of this type leave their students on their own in content acquisition by selecting lesson content that is new to them without further content preparation.

3.4.2. Type 2: Low PCK but High Blended TK Domains

Pre-service biology teachers with low PCK but high TPK and TPACK (1) link the use of technology more purposefully with the learning objectives and the subject content structure, describing digital technology as a supportive tool in subject teaching. Nevertheless, (2) due to the novelty of the use of technology, they are concerned about the students' cognitive overload, leading them to focus on scaffolding the use of technology.

(1) Connection between Content and Technology

> "*So I always look a bit for benefits. (. . .) You have to see how it [the use of technology] works in a targeted way and where it might turn into something negative.*"

(LR RA27JR).

Most pre-service biology teachers assigned to this pattern draw a link between subject content and the use of technology. For example, the use of technology is "examined for its added value" (LR EB09GG) in lesson planning. Pre-service biology teachers describe the usefulness of digital technology mostly towards lesson objectives and occasionally for the characteristics of the subject content. Regarding the lesson objectives, pre-service biology teachers often describe the deepening or consolidation of the subject content through students' active or intensive engagement with the subject content during instructional video planning and creation, but also the structuring property of planning an explainer video in the content-related learning process. Regarding the characteristics of the respective biological subject content, some emphasize the added value of the use of technology for the (multimodal) illustration of complex biological relationships or abstract concepts and dynamic processes in lesson planning and reflection.

(2) Novelty of the Technology Use

> "*I could not estimate how fast they would be because I had never done it before. [...] However, I did not know whether the fact that I had prepared so much material meant that it might be too much and that it perhaps would take away a bit of their imagination to think ahead themselves.*"
>
> (LR RA27JR)

Some pre-service biology teachers assume during lesson planning that the students have already internalized or mastered the subject content and do not consider it further relevant to the lesson. In contrast, pre-service biology teachers describe concerns about students' cognitive overload in the lesson due to the novelty of the teaching method or the software application. In this respect, content-related aspects are only occasionally considered as a learning challenge and generally in combination with technological aspects. In lesson reflection, concerns are also attributed to a lack of experience in using digital technology in class, which results in difficulties with estimating students' technological skills. In this regard, the pre-service biology teachers express concern, for example, that "the students might press something wrong and are overwhelmed" (LR EB09GG) as they are "overwhelmed with everything new" (LR FI13CS). As a result, they regard it as crucial "to prepare the students for the creation of the explainer videos" (LP FI13CS) and to provide them with (mainly technological) support to counteract this excessive demand.

3.4.3. Commonalities between the Two Types

In both types, the selection of the specific hardware and software for video creation is based on the pre-service biology teachers' confidence regarding the respective digital technology rather than instructional considerations regarding the subject content. Pre-service biology teachers select software they already know and can implement without further preparation. Many of them consider the engagement with digital technology to be too complex for students. Thus, they deliberately reduce the subject content to free up resources for engagement with digital technology.

3.4.4. Low Student Activation but High Lesson Structuring

Pre-service biology teachers that emphasize lesson structuring while neglecting student activation are characterized by the following points:

(1) Concerns with the use of technology regarding potential lesson failure;
(2) Concerns with a loss of control regarding the high level of students' autonomy;
(3) An orientation towards the creation of high-quality explainer videos instead of the creation process.

The cases allocated to this pattern can essentially be assigned either to type 2, to neither of the two types, or occasionally to type 1. Accordingly, a heterogeneous constellation of pre-service biology teachers shares this overarching pattern.

(1) Concerns with the Technology Use

> "*I found it extremely difficult to estimate how skilled they [the students] are in dealing with digital media (. . .). I was extremely unsure of how much help and explanation was needed, whether a work phase would even occur or whether it would simply be too much work and everyone would just press the buttons in a muddle.*"
>
> (LR KE04JG).

Concerns regarding the lesson failure became apparent in lesson planning and reflection. The pre-service biology teachers found it challenging to estimate students' content- and technology-related skills (predominantly type 2; see Section 3.4.3). Moreover, they were overwhelmed by the challenges of the use of technology or missed guidance from role models or clear guidelines at the internship school (mainly type 1; see Section 3.4.3). In addition, they expressed concerns with time management regarding the video creation due to overburdening the students with digital technology and content. Consequently, pre-service biology teachers emphasized providing sufficient time, systematic instruction, and clear guidelines for video creation to ensure "that every single step is clear" (LR WE06CM).

(2) Concerns about Loss of Control

> "*I was very nervous because I also find it difficult to hand over responsibility. (. . .) it's always like 60:40 whether it works out or not when you hand over responsibility or not. And it usually doesn't work out.*"
>
> (LR MA07CG).

Many pre-service biology teachers expressed concern with the increased degree of students' autonomy and the associated loss of control throughout the lesson. They worry that this loss of control and lack of structure will lead to a failure of the lesson. As a result, a small-step lesson structuring is derived and preferred over student activation. In some cases, pre-service biology teachers assume that student activation results from the use of technology itself and therefore does not require action on their part. As this aspect is frequently associated with pre-service biology teachers' difficulties in estimating students' skills, it was predominantly met by type 2 and partly by type 1.

(3) Product Orientation instead of Process Orientation

> "*So, my most important issue, the most important aspects, where I hoped that something would emerge, or rather that each group would definitely produce a video.*"
>
> (LR WE30VJ).

When asked about the central objective of a lesson, the pre-service biology teachers often focus on the product and less on the process of video creation. This product-oriented focus is also evident in lesson planning, where the pre-service biology teachers concentrate mainly on the quality of the explainer videos in terms of instruction and content. To ensure this quality, the pre-service biology teachers set clear guidelines for the video, which restrict students' autonomy. This aspect tends to be associated with focusing on surface characteristics of the lesson and was observed more frequently in pre-service biology teachers from type 1.

3.4.5. Discontinuities between the Data Sets

In the following section, the discontinuities between lesson planning, implementation, and reflection on the (1) TPACK, (2) PCK, and (3) TPK domains identified in Section 3.3 are analyzed based on the qualitative data.

(1) Discontinuities in the TPACK Domain

> "*The mentor said, okay, that's where we are in the book. That's actually the only thing that comes to mind in this context.*"
>
> (LR RA27JR).

In lesson reflection, pre-service biology teachers mainly justified the selection of the subject content on the basis that it fits into their mentor's current teaching unit. In addition, several pre-service biology teachers reported a lack of influence on the selection of subject content during the internship semester. Instead, they were bound to their mentor's subject distribution plans.

(2) Discontinuities in the PCK Domain

The pre-service biology teachers consider the relevance of the subject content frequently in lesson planning but rarely in lesson implementation. They explicate this aspect mostly in the theoretical parts of the lesson plan (e.g., instructional planning or subject analysis) or in curricular reference. Only one of the pre-service biology teachers addresses the relevance of the subject content again in the methodological planning and the outline of the concrete lesson. Indicators regarding the relevance of the subject content in the students' lives, which are addressed in these rather concrete parts of the lesson plan, are mainly implemented within lessons.

(3) Discontinuities in the TPK Domain

Most pre-service biology teachers consider the support for students regarding content-related and technological issues in lesson planning. Many pre-service biology teachers solely focus on addressing technological problems in lesson planning and stress the challenges that arise from the complexity of the video creation tasks. They emphasize that unclear instructions "can lead to the group working only with difficulty or not at all" (LP BL13MR). However, pre-service biology teachers frequently mention providing demand-oriented support without explicitly assigning it to one of the areas mentioned, stating that the teacher is available in the classroom to answer any questions that arise. These cases were coded according to all three indicators.

4. Discussion

This study aimed to investigate how pre-service biology teachers apply their TPACK in teaching using digital technology. For this purpose, a comparatively large sample of pre-service biology teachers (n = 42) was accompanied in the field following an ecologically valid intervention at the university based on empirical criteria for TPACK development [15]. TPACK was collected taking into account the context and by triangulation of lesson planning, implementation, and reflection. This approach enabled authentic and comprehensive insights into the enactment of pre-service biology teachers' theoretical TPACK in real classroom situations.

The findings revealed that pre-service biology teachers are able to apply certain aspects of PCK, TPK, and TPACK in classroom practice. However, they tend to focus more on specific domains while neglecting others. Specifically, in lesson planning, pre-service biology teachers emphasized PCK less than TPK. In lesson implementation, pre-service biology teachers had less emphasis on PCK compared to both TPK and TPACK. Similar to the findings of DeCoito and Richardson [7], the pre-service biology teachers in this study predominantly implemented digital technology from a technological perspective and need to consider PCK more holistically.

Some of the pre-service biology teachers tend to select hardware and software based on the required preparation rather than considering their potential for teaching complex, abstract, and/or dynamic biological subject content. Moreover, they reduce content-related complexity deliberately to reserve students' cognitive capacity for using digital technology. These results indicate that the respective pre-service biology teachers struggle with drawing a link between teaching the subject content and the use of digital technology. Pringle et al. [8], Valtonen et al. [56], and von Kotzebue [23] report similar findings. Ocak and Baran [55] came to different results regarding in-service teachers. The in-service teachers in their study particularly emphasized the subject content and PCK aspects when making decisions related to the use of technology. This may be explained by their extensive experience, enabling them to draw upon more sophisticated PCK. Although they had previously taken part in an intervention that emphasized benefits of digital technology in science teaching, the pre-service biology teachers participating in our study did not address PCK aspects accordingly. One possible reason for this could be that the specified emerging new use of technology could have stimulated a technology focus among them. Although the alignment between selected subject content and digital technology is comparatively high in lesson implementation, this is rarely justified in lesson planning or lesson reflection. Accordingly, different explanations for this can be considered as follows: (1) the characteristics of the selected subject content coincidentally align with the use of digital technology, or (2) the mentors at the internship school strongly influenced the alignment process.

The study identified two types of pre-service biology teachers' TPACK enactment, discontinuities between the data sets, and an overarching pattern. The following subsections discuss these results in detail and relate them to the current state of research.

4.1. Types of Technology Use among Pre-Service Biology Teachers

The split-focus type generally subordinates the content-related domains (PCK and TPACK) to TPK. This group systematically separates the subject content from the use of technology and, in this respect, regards the use of technology as an independent and equivalent learning content of the lesson sequence. Consistent with the findings of Kapici and Akcay [53], the respective pre-service biology teachers report concerns regarding technology usage and justify their concerns by stating that they did not feel ready for the use of technology [7]. This is primarily linked to their low confidence in using digital technology, as pre-service biology teachers describe themselves as not technologically savvy. Accordingly, they focus on surface characteristics (e.g., time management and technological preparation of the students) to guarantee that the lesson runs without disruptions on the surface. This focus on surface characteristics when using digital technology in the classroom has been observed particularly among pre-service teachers with low enacted TPACK [43].

The novelty-focus type focuses on the technology-related categories (TPK and TPACK) while subordinating PCK. Compared to the split-focus type, this type demonstrates a purposeful link between digital technology and subject content. Pre-service biology teachers describe digital technology as a valuable instructional tool for consolidating the subject content and emphasize the added value of digital technology regarding characteristics of their selected subject content. Nevertheless, these pre-service biology teachers perceive the use of technology as a primary challenge to students' learning due to the novelty of the instructional method or the software used. They find it challenging to estimate students' technological competencies and are concerned with students' cognitive overload. Supporting the findings of several studies in the field of enacted TPACK, the pre-service biology teachers' unfamiliarity with the use of technology results in a focus on technological guidance for the students and neglecting PCK aspects accordingly [43,51–53]. In contrast to the results of Akyuz [43], this also applies to pre-service teachers who have already achieved an understanding of TPACK as a distinct domain.

4.2. Identified Pattern

In both lesson planning and lesson implementation, subcategories dealing with student activation are significantly less pronounced than subcategories dealing with lesson structure. Correspondingly, von Kotzebue [23] reports low levels of students' cognitive activation (predominantly levels of reproduction and reorganizing) and self-determination in pre-service science teachers' technology-enhanced lesson plans. However, a shift towards teacher-centered instead of student-activated teaching was also observed among experienced in-service teachers using novel digital technology in class for the first time [54,55]. This pattern is described as overarching since pre-service biology teachers from both the split-focus and novelty-focus types and pre-service biology teachers assigned to none of these types share it.

Overall, however, there are comparatively more cases of the novelty-focus type than the split-focus type assigned to the pattern. Figure 2 depicts the identified pattern connecting the two types. Pre-service biology teachers assigned to this pattern shared three aspects: (1) concerns with the use of technology, (2) concerns with loss of control, and (3) high product orientation. While (1) occurred equally in both types, (2) was observed comparatively more frequently in the novelty-focus type and (3) more frequently in the split-focus type. Accordingly, pre-service biology teachers are insecure in using technology for various reasons, seeking to maintain control of the lesson and focusing rather on the product (explainer video) than on the students' learning process. To counteract insecurities and to gain control over the lesson, pre-service biology teachers provide comprehensive support structures and clear instructions while avoiding self-directed student activity.

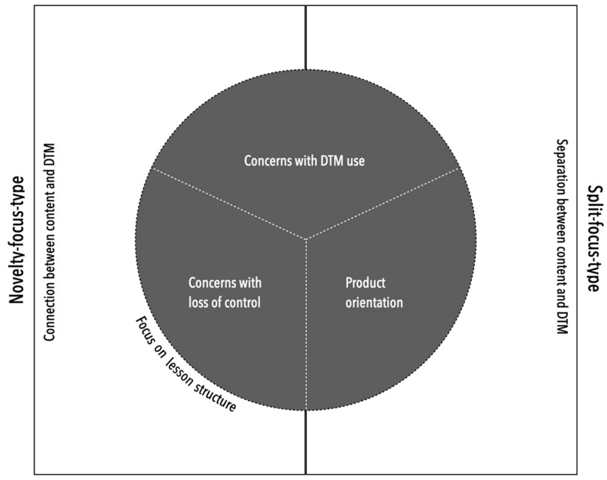

Figure 2. Illustration of the identified types and pattern in interaction.

4.3. Identified Discontinuities within the Data Sets

Like Yeh et al. [57], we also found discontinuities between the data sets. These discontinuities could be attributed to the different demands of the teaching phases. For example, the lesson plan provides clear directives as stipulated by the educational institution, while lesson implementation involves spontaneous practical obstacles, and lesson reflection requires the ability to introspect.

Thus, pre-service biology teachers tend to apply superficial rule-based approaches in the theoretical parts of lesson planning, which are not transferred to lesson implementation or taken into account in lesson reflection. Conversely, indicators that were previously considered in lesson planning or reflection were not identified in lesson implementation. This could be due to the guidance of the mentors during the internship semester and/or the pre-service biology teachers' ability to react spontaneously to unexpected practical challenges.

4.4. Limitations

The sample size (n = 42) limits the study results. However, increasing the sample size was impossible due to the high complexity of the data collection and analysis process, the underlying data itself, and the EnTPACK rubric. The study was situated in specific contextual conditions, leading to context-specific definitions of the TPACK domains. Nevertheless, the results are transferable to similar application contexts. In addition, this study represents a field study, and it was impossible to create identical conditions. For instance, pre-service biology teachers were mentored by in-service teachers of varying competence in using digital technology who accompanied them in lesson planning, implementation, and reflection during the internship semester. As a result, decisions relevant to the study (e.g., the selection of subject content) may have been influenced by this mentoring. However, the study thus fulfills the requirement of ecological validity.

4.5. Implications for Practitioners

In line with the findings of Tondeur et al. [26], the results of this study indicate that TPACK development represents a highly individual process that a one-size-fits-all approach cannot facilitate. The present study provides new insights into pre-service biology teachers' TPACK enactment. The results contribute to a systematization in the diverse field of TPACK enactment, thus providing the basis for deriving individual support strategies.

However, further research using qualitative data to explain quantitatively identified patterns is needed to investigate the complex interactions between intrinsic variables (attitudes, values, epistemic beliefs), environmental conditions (role models, values, school facilities), and TPACK enactment.

The study reinforces recommendations on TPACK development from previous studies. Accordingly, emerging digital technologies need to be integrated into PCK programs with a focus on the blended PK domains [13,43,48], explicitly emphasizing the supporting role of digital technology as a tool in teaching subject content [56].

4.6. Implications for Scientists

The discontinuities within the data sets show that TPACK enactment needs to be triangulated based on the combination of different data sets, including lesson planning, implementation, and reflection [31,49,51].

Since enacted TPACK expresses differently concerning various contextual conditions on site [44], it is mandatory to consider contextual factors and qualitative data to identify causal relationships beyond speculative assumptions. In this respect, the consideration of cognitive and affective dispositions of pre-service science teachers could be particularly informative [42].

As professional knowledge may occur tacitly in interactive decision-making during lesson implementation [42], it might also be helpful to collect data on pre-service teachers' reflection in action as an additional assessment method in TPACK enactment research.

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Appendix A. The Categories, Subcategories, Criteria, and Indicators of the EnTPACK Rubric

Categories	Subcategories	Criteria	Indicators (Weight)
TPACK	(TPACK alo) **Alignment of the use of digital technology with the lesson objective(s)** The pre-service teacher (PST) **focuses on content-related learning objectives**, that are **appropriately facilitated through the use of digital technology** (student-generated explainer videos).		(TPACK alo-a) The video creation task focuses on the explanation of a biological or scientific process/content by the students. (2)
			(TPACK alo-b) The lesson serves to consolidate/deepen a subject content that has previously been taught. (3)
			(TPACK alo-c) The PST relates their content-related learning objective to using digital technology. (3)
			(TPACK alo-d) The PST emphasizes content-related learning objectives over the promotion of media literacy. (2)
			(TPACK alo-e) (Planning and Reflection) The PST considers alternative methodological-medial options to achieve the content-related learning objectives. (1)
			(TPACK alo-f) There is a discontinuity between the content-related learning objective(s) and the teaching. The teaching contradicts the content-related learning objective. (−2)
			(TPACK alo-g) The PST focuses more on the product than on the process of video creation. (−1)
	(TPACK asc) **Alignment of the use of digital technology with the subject content** The PST selects a **subject content that particularly benefits from the use of digital technology**.		(TPACK asc-a) The selected subject content is self-contained. An understanding of the subject content is possible with the available materials without the inclusion of additional content. (1)
			(TPACK asc-b) The PST limits the scope of the selected subject content so that it can be presented in a short explainer video. (2)
			(TPACK asc-c) The selected subject content is sufficiently complex (content needs to be related/connected). (3)
			(TPACK asc-d) The selected subject content exhibits spatial and/or temporal changes (dynamics). (3)
			(TPACK asc-e) The PST connects the selected subject content and the use of digital technology. (1)
			(TPACK asc-f) The subject content is so rich in detail and complexity that visual representation is impeded. (−2)

Categories	Subcategories	Criteria	Indicators (Weight)
PCK	(PCK cs) **Content structuring**	(PCK cs1) The PST ensures **appropriate transparency (clarity) of the content-related lesson objectives** for the students	(PCK cs1-a) The learning objective and/or the assignment are communicated to the students comprehensibly (appropriate to the addressees). (2)
			(PCK cs1-b) The learning objective and/or the assignment are visibly fixed for the students. (1)
			(PCK cs1-c) The PST formulates content-related requirements for the explainer video. (2)
			(PCK cs1-d) The PST formulates an individual objective or arbitrary requirements for the students ("Do your best"). (If not given, then the other indicators are evaluated. If given, then 0.)
		(PCK cs2) The PST focuses specifically on **central key aspects of the subject content**.	(PCK cs2-a) The PST emphasizes key aspects of content (e.g., emphasizes their importance). (2)
			(PCK cs2-b) The focused key aspects are of central importance for the content-related learning objective/for understanding the subject content. (2)
			(PCK cs2-c) The PST distinguishes the key aspects from non-essential aspects. (1)
			(PCK cs2-d) The PST connects the key aspects with the rest of the course. (1)
			(PCK cs2-e) The PST incorporates aspects into the lesson that are incidental to the content-related learning objective. (−1)
		(PCK cs3) The PST **uses technical language appropriately** in the lesson.	(PCK cs3-a) The PST defines the technical terms to be used in the explainer video and/or to be consolidated during video creation. (2)
			(PCK cs3-b) The selected technical terms are necessary to achieve the lesson objective(s) and/or to understand the subject content. (2)
			(PCK cs3-c) The video creation task requires a verbal explanation of the subject content. (2)
			(PCK cs3-d) The PST refrains from using technical terms that are not required to achieve the lesson objective(s) and/or to understand the subject content. (1)
			(PCK cs3-e) The PST misuses technical terms in the lesson. (−2)

Categories	Subcategories	Criteria	Indicators (Weight)
		(PCK cs4) The PST ensures that the students receive **appropriate content-related feedback**.	(PCK cs4-a) The PST defines criteria for feedback. (2)
			(PCK cs4-b) The feedback is based on the defined criteria. (2)
			(PCK cs4-c) Students have access to the criteria during video creation. (2)
			(PCK cs4-d) The feedback and/or the criteria focus on the content-related learning objective(s). (2)
			(PCK cs4-e) The feedback and/or criteria include informative as well as practical advice for further learning or editing. (1)
			(PCK cs4-f) The feedback is appreciative. (2)
			(PCK cs4-g) The criteria are formulated unclearly. (−2)
	(PCK ca) **Cognitive activation**	(PCK ca1) The PST provides an **authentic setting** for the video creation	(PCK ca1-a) The explainer videos are directed at a realistic audience. (1)
			(PCK ca1-b) The PST provides authentic stimuli for video creation. (2)
		(PCK ca2) The PST ensures that the students **engage with the relevance of the subject content**.	(PCK ca2-a) The relevance of the subject content (e.g., individual, societal, or vocational) is discussed. Either by the teacher or as part of the video creation task by the students themselves. (1)
			(PCK ca2-b) A (e.g., individually, societally, or vocationally) relevant question or problem constitutes the initial basis of the video creation task. (1)
			(PCK ca2-c) The PST provides a context (e.g., phenomenon or history) to the subject content. (1)
		(PCK ca3) The PST enables the students to **transfer** their **previously acquired knowledge** appropriately via the video creation task.	(PCK ca3-a) The PST activates the students' relevant prior knowledge. (1)
			(PCK ca3-b) The PST provides (at least) one prototypical example for the explainer video. (1)
			(PCK ca3-c) The video creation task allows the students to determine the content structure of their explainer videos independently. (1)
			(PCK ca3-d) The PST supports the students in structuring the content according to their individual needs. (1)

Categories	Subcategories	Criteria	Indicators (Weight)
			(PCK ca3-e) The PST guides the students in reproducing defaults. (−1)
			(PCK ca3-f) The task does not require the students to use their content knowledge. (−1)
TPK	(TPK scl) **Scaffolding cognitive load**	(TPK scl1) The PST **reduces the students' cognitive load** induced by the **handling of digital technology**.	(TPK scl1-a) The PST considers the technology-related (pre-) experiences of the students. (2)
			(TPK scl1-b) The PST selects an appropriate software for the video creation task. (1)
			(TPK scl1-c) The PST introduces the students to the essential functions of digital technology that are mandatory for the video creation task. (2)
			(TPK scl1-d) The PST supports and advises the students on questions regarding digital technology as needed. (3)
			(TPK scl1-e) (Planning and Reflection) The selected digital technology is reflected in instructional and/or cognitive psychological aspects. (1)
		(TPK scl2) The PST **reduces the students' cognitive load** induced by the **planning and design** of the explainer video.	(TPK scl2-a) The PST points out that the explainer videos' design quality is not the lesson sequence's focus. (2)
			(TPK scl2-b) The PST provides the students with exemplary production materials for content presentation. (2)
			(TPK scl2-c) The PST introduces the students to the selected production method. (2)
			(TPK scl2-d) The PST supports and advises the students with planning or design problems and/or questions as needed. (1)
			(TPK scl2-e) The PST provides the students with a structural basis for planning their video. (2)
			(TPK scl2-f) The PST formulates a variety (>4) of design criteria and/or established design criteria are irrelevant to understand the subject content. (−2)
		(TPKscl3) The PST **reduces the students' cognitive load** induced by the **self-organized group work**.	(TPK scl3-a) The PST structures the video creation task into subtasks and provides them to the students. (1)
			(TPK scl3-b) The PST regulates the group size to small groups (max. 3–4 students per group). (1)

Categories	Subcategories	Criteria	Indicators (Weight)
			(TPK scl3-c) The PST supports the groups in case of questions and/or problems concerning the group organization. (2)
			(TPK scl3-d) (Planning and Reflection) The PST justifies the constellation of the group formation. (1)
	(TPK il) **Interactive learning** The PST promotes an **active, constructive and interactive use of digital technology** by the students.		(TPK il-a) The PST encourages students to engage in content discussions on and beyond the subject content. (3)
			(TPK il-b) The PST integrates phases of co-construction and intra-group discussion on content firmly into the lesson. (3)
			(TPK il-c) The PST regulates the use of digital technology in order to achieve a constructive and productive handling of the students. (1)
			(TPK il-d) The PST identifies the activation and collaboration of the students as a key potential of the use of digital technology. (2)
			(TPK il-e) The PST asks the students to argue for their statements. (2)
	(TPK tm) **Time management** The PST ensures that the **lesson is appropriately timed**.		(TPK tm-a) Time allocation is appropriate to the learning objective(s). (2)
			(TPK tm-b) The students are given enough time to plan and create the video (at least 40 min). (3)
			(TPK tm-c) The PST considers alternative approaches in the absence of time. (1)

Appendix B. Heatmap of the Rubric Values for the Total Sample on a Likert Scale from 0 to 3

Cases	Student Activation		Lesson Structuring		PCK		TPK		TPACK	
	LP	LI	LP	LI	LP	LI	LP	LI	LP	LI
SA27LK	1.50	0.83	1.69	1.86	0.88	0.96	2.11	1.78	0.50	1.00
BL05PW	2.00	1.17	1.83	1.94	1.25	0.92	2.33	2.11	1.00	1.00
RA25NR	0.83	1.00	2.31	2.53	1.46	1.63	1.89	2.11	3.00	2.50
FR07SS	1.33	1.17	2.53	2.56	1.96	2.17	2.11	1.89	1.00	2.50
KA04GT	0.67	1.50	1.25	2.28	1.04	1.25	1.00	2.44	0.00	2.00
EH15SE	1.67	1.00	2.28	1.72	1.42	1.25	2.44	1.56	0.50	0.50
LI13VB	1.00	0.83	1.67	1.75	1.00	0.46	1.67	2.00	1.00	0.50
SA03TD	0.83	1.33	2.11	2.25	1.83	1.71	1.44	2.00	2.00	2.00
TE09SM	1.83	1.50	2.06	2.03	1.58	1.38	2.22	2.11	1.50	1.50
ÜB02SB	1.50	1.00	2.61	2.61	1.75	1.75	2.44	2.11	1.00	1.50
SA08AP	1.50	0.83	2.47	2.61	1.88	1.58	2.22	2.11	0.50	1.50

Cases	Student Activation		Lesson Structuring		PCK		TPK		TPACK	
	LP	LI	LP	LI	LP	LI	LP	LI	LP	LI
RI06SB	1.83	1.50	1.56	1.86	1.83	1.63	1.56	1.78	1.50	1.50
RE04SP	1.17	0.33	1.08	0.86	0.29	0.46	1.67	0.78	0.50	1.50
KE04JG	0.83	0.17	1.42	2.17	0.96	0.92	1.33	1.67	1.00	1.50
FR07AH	1.33	1.00	2.19	1.67	1.46	1.00	2.11	1.67	1.00	2.00
SI10MG	1.83	0.83	2.25	2.19	1.71	0.96	2.33	2.11	2.00	2.50
SI27AA	1.17	1.50	0.86	1.17	0.79	0.75	1.11	1.67	2.00	2.00
TU23KP	1.00	1.00	2.28	2.31	1.75	1.63	1.78	1.89	0.50	1.00
WA16AA	0.50	1.33	1.81	2.08	0.88	0.96	1.56	2.33	1.50	2.50
WE02NA	1.67	1.00	0.53	1.53	0.79	1.13	1.11	1.44	2.00	1.00
WE06CM	1.00	1.33	2.11	1.75	1.50	0.96	1.78	2.00	1.50	2.50
WE30VJ	1.67	0.33	2.06	2.28	1.42	1.08	2.22	1.78	1.50	1.00
FR05MH	0.33	0.83	1.89	1.39	0.83	0.58	1.56	1.56	2.50	2.50
LE03SE	1.17	0.50	0.50	0.53	0.92	0.63	0.67	0.44	2.00	2.00
WE08EB	0.67	1.17	2.06	2.31	1.42	1.29	1.56	2.22	0.50	2.00
BA16PM	1.67	1.67	2.50	2.69	1.92	2.04	2.33	2.44	1.50	2.50
BL13MR	1.00	1.83	2.14	2.44	1.38	1.83	1.89	2.44	1.00	2.00
HO03AH	1.00	0.83	2.22	2.17	1.50	1.08	1.89	2.00	1.50	2.00
IL03LG	0.50	1.50	2.50	2.61	1.75	1.75	1.67	2.44	1.00	2.50
MA07CG	0.33	1.33	1.36	1.67	0.71	0.83	1.11	2.00	1.00	2.50
OF25SS	1.00	0.83	1.97	1.67	1.13	0.83	1.89	1.67	2.50	1.50
RA11SC	0.83	0.83	2.17	2.53	1.08	1.46	2.00	2.11	1.50	2.00
RA22XG	1.00	0.67	1.86	2.17	1.13	1.42	1.78	1.67	1.00	2.00
RA27JR	0.83	1.50	1.69	1.86	0.71	1.13	1.78	2.11	2.50	2.50
SI15CH	0.17	0.33	1.97	2.17	0.79	1.08	1.56	1.67	1.50	2.50
WE05PG	0.33	0.83	1.78	1.69	1.33	1.21	1.11	1.44	1.50	3.00
BA15MW	1.67	0.33	2.39	1.83	1.92	0.58	2.22	1.67	2.00	1.50
EB09GG	1.00	1.33	2.17	1.83	1.25	1.08	2.00	2.00	2.00	1.50
FI13CS	0.00	0.00	1.58	1.67	0.38	0.50	1.33	1.33	2.00	2.50
KO20ST	0.83	0.83	2.53	2.00	1.46	1.33	2.11	1.67	2.00	2.50
OC15AF	1.50	1.50	2.25	1.94	1.38	1.25	2.33	2.11	1.50	1.50
WE13IR	1.00	1.00	0.92	1.56	0.88	1.00	1.00	1.56	1.50	2.50
	= low performer (0–0.99)			= middle performer (1.00–1.99)				= high performer (2.00–3.00)		

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