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Technology Implementation in Pre-Service Science Teacher Education Based on the Transformative View of TPACK: Effects on Pre-Service Teachers' TPACK, Behavioral Orientations and Actions in Practice

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Abstract: Teaching with and about technology is part of science teachers' 21st century skills. To foster technology-enhanced practice, teachers need to acquire both technological pedagogical content knowledge (TPACK on action) and positive behavioral orientations toward technology exploitation. However, it remains unclear if the gained knowledge is applied in practice (TPACK in action). Therefore, studies are required to investigate the interplay of programs promoting TPACK on action, behavioral orientations, and resulting TPACK in action. This paper presents an approach that explicitly links pre-service science teachers' pedagogical content knowledge (PCK) with TPACK development in two undergraduate modules, following the transformative view of TPACK. TPACK on action and behavioral orientations are captured through a questionnaire at three points in time. Additionally, lesson plans are analyzed to evaluate the quality of technology use and cognitive engagement, approximating TPACK in action. The results show a significant increase in pre-service science teachers' (N = 133) self-rated TPACK on action and behavioral orientations between pre- and post-test, with moderate to large effects. Moreover, the analyses of lesson plans reveal a high quality of technology exploitation in the planned lessons, indicating distinctive TPACK in action after attending the modules. This theory-based approach is supported by empirical data, and highly regarded by participants, making it a successful model for course redesign at other universities.

Keywords: TPACK; theory of planned behavior; pre-service teacher education; science education; curriculum development

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1. Introduction

Digital transformation has progressed rapidly in everyday and working life in recent decades and has also found its way into the classroom. Especially science education has a great potential for the multifaceted use of technology, not only due to the proximity of science to technology itself but also because of its advantages for teaching and learning. For example, internal and external measurement sensors and devices can be used as alternatives for traditional lab equipment; interactive simulations and remote or video experiments can enable students to explore experimental setups that cannot be realized in the classroom; data analysis and presentation software can contribute to minimizing barriers in dealing with measurements; and modeling software and virtual and augmented reality applications can be applied to model and visualize interrelationships between quantities.

In order to be able to integrate technology purposefully into science education, pre-service science teachers need to develop and interconnect content knowledge (CK) and pedagogical knowledge (PK), as well as technological knowledge (TK), forming technological pedagogical content knowledge (TPACK) [1,2]. Accordingly, universities face the challenge of redesigning existing study programs to meet these requirements. Today, technology is integrated into teacher education in multiple ways, from (elective) add-on modules to the implementation of technology into existing modules [3]. Considering the transformative view of TPACK [4–9], especially the implementation of technology into science education modules seems to be most promising, as this allows the development of PCK and TPACK on action simultaneously [8–14]. Additionally, pre-service science teachers are offered the opportunity to gain positive (theoretical and/or practical) experiences with technology, which, in turn, promote advantageous positive behavioral orientations toward technology exploitation in science education [15–17]. In this context, several authors emphasize the theory of planned behavior (ToPB [18]) as a valid framework to assess (pre-service) teachers' intentions to implement technology into their classroom practice [19–24]. Nevertheless, none of these studies go beyond the intended use of technology and address how teachers implement technology into science education (TPACK in action). This is of particular relevance, however, as it is known that teachers' TPACK on action is often not consistent with their (future) actions in the classroom [25,26]. Therefore, studies combining measures of (pre-service) teachers' TPACK on action, their behavioral orientations and resulting TPACK in action represent a research desideratum [3,25–27]. Additionally, mixed-methods approaches that collect and combine quantitative and qualitative data in order to compensate for the respective limitations of the individual instruments are needed [3,27].

To address this challenge, the current study aims to investigate how the implementation of technology according to the transformative view of TPACK in the science teacher education program at the Leuphana University Lüneburg influences the TPACK of pre-service science teachers both on action and in action, as well as their behavioral orientations.

2. Theoretical Framework

In the following sections, we briefly outline the TPACK framework and provide an overview of TPACK assessment in empirical research. In so doing, we distinguish between TPACK on action and TPACK in action and discuss methodological approaches to investigate both.

2.1. TPACK

Based on Shulman's PCK model [28], teachers' professional knowledge about the purposeful integration of technology in class can be described by the TPACK framework [1,2], which distinguishes between pedagogical knowledge (PK), content knowledge (CK), technological knowledge (TK) and the resulting hybrids first (PCK: pedagogical content knowledge, TCK: technological content knowledge, TPK: technological pedagogical knowledge) and second order (TPACK: technological pedagogical content knowledge), as shown in Figure 1.

Building on PCK research by Grossman [29], Niess [30] conceptualized TPACK as consisting of four elements: (1) an overarching conception of teaching a subject with technology, (2) instructional strategies and representations for teaching with technologies, (3) students' understandings, thinking and learning in a subject with technology, as well as (4) curriculum and curricular materials. Other authors such as Canbazoğlu Bilici et al. [31] added a fifth element: (5) knowledge of assessment with technology, in accordance with Magnusson et al.'s [32] PCK elements.

Initial research on TPACK focused on the framework itself, e.g., the internal structure or interpretation. In particular, two contrasting perspectives on the relation between TPACK dimensions have emerged among researchers [33,34]: the integrative and the transformative view. Following the integrative view, TPACK arises from the integration of all TPACK dimensions (CK, PK, TK, PCK, TCK and TPK). In contrast, the transformative view assumes that TPACK is formed by the first hybrids PCK, TCK and TPK, which themselves depend on CK, PK and TK. Current empirical studies favor the transformative view of TPACK already described theoretically by Mishra and Koehler [2,4–8,35–38]. Nevertheless, only in a study by Pamuk et al. [6], all first-order hybrids were found to have a significant influence on TPACK. All other studies only found two of the three first-order hybrids to be positive predictors for TPACK, mainly PCK and TPK [4,5,7,8,33].

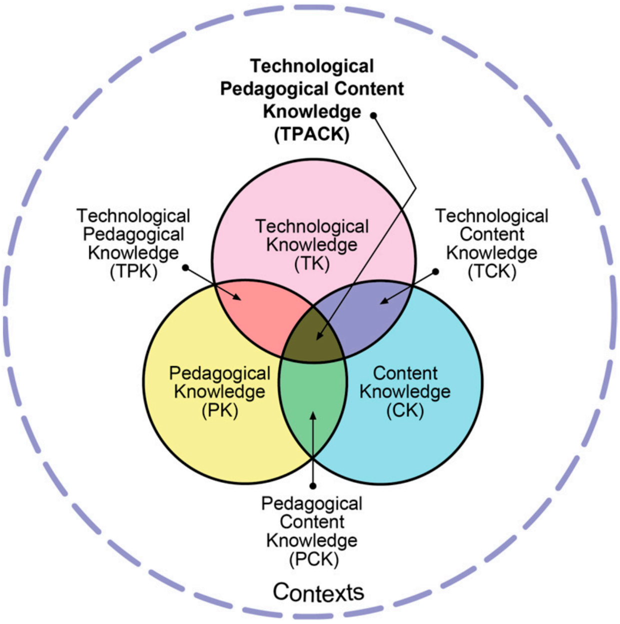

Figure 1. TPACK framework (reproduced by permission of the publisher, © 2012 by tpack.org).

In recent years, TPACK research has shifted from investigating the framework itself to the application of the framework as well as potential extensions [39–41]. Various methods and approaches have been developed to capture TPACK, especially in the context of skill development of (pre-service) science teachers, as discussed in the following section.

2.2. TPACK Assessment in Empirical Research

One goal of current science teacher education programs is for pre-service teachers to develop the necessary skills to integrate technology purposefully into their practice. Corresponding empirical research on TPACK (development) uses various measures, such as self-assessment questionnaires [42–52], performance assessment [25,31,52–54], analysis of lesson plans [14,31,55,56] and lesson observations [57–59].

These measures can be distinguished into two groups: TPACK self- and performance assessments capture teachers' knowledge on action. Analysis of lesson plans and lesson observations are used to describe teachers' practice and, therefore, can be understood as knowledge in action [60]. TPACK on and TPACK in action are linked in that teachers' knowledge on action forms the basis for planning and teaching topic-specific lessons [61], which integrate technology and is, thus, a prerequisite for TPACK in action.

2.2.1. TPACK on Action

Teacher self-assessments are widely used instruments to capture TPACK on action. Not only are they of high practical applicability, but they also allow for assessing teachers' confidence in implementing technology and drawing conclusions about their technology-related self-efficacy beliefs [62,63]. However, self-assessment questionnaires often face inherent methodological limitations and present constraints related either to validity or reliability [7]. Some of the instruments only capture selected TPACK dimensions [64,65] or considerably vary in the number of items per TPACK dimension [47,49]. Moreover, subject-independent item formulations, such as "in my content area" [47] or "in my teaching subject" [45], can distort the results, as in some countries (pre-service) teachers study/teach more than one subject.

As several studies have shown, TPACK self-assessments often lack a satisfactory correlation with more objective measurements [25,31,53] and crucially differ from teachers' actions observed in the classroom [25,26]. In order to obtain a meaningful assessment of (pre-service) science teachers' TPACK, on the one hand, and their technology-related self-efficacy beliefs, on the other hand, it is, therefore, necessary to combine TPACK on action self-assessments with more objective measures that take into account classroom practice and, thus, teachers' TPACK in action. Following this, mixed-methods approaches, which combine self-reported TPACK with more objective measurements, have become prominent in recent studies [66].

2.2.2. TPACK in Action

One approach to capture (pre-service) teachers' TPACK in action is the use of TPACK rubrics to analyze authentic data sources such as lesson plans or observations. However, these rubrics are subject to limitations. For example, existing TPACK rubrics for lesson plans, which follow descriptions of PCK elements [32], adapted for TPACK, sometimes fail to cover all TPACK elements and determine teachers' TPACK in action level, e.g., by the lowest score across all TPACK elements [56]. Other existing TPACK rubrics assign an overall value to TCK, TPK and TPACK [55] while neglecting PCK. In both cases, potentially varying quality in technology exploitation is neglected and, as in the second case, the related instructional quality is not captured.

It becomes evident that TPACK in action is a rather difficult construct to grasp. Instead, the quality of technology exploitation, which can be understood as a manifestation of teachers' TPACK in action, can be assessed from lesson plans or observations by the SAMR [67] and the ICAP [68,69] framework, respectively (see Table 1).

Table 1. Levels of the SAMR and ICAP frameworks to describe the quality of technology exploitation in practice.

	SAMR Framework [67]		ICAP Framework [69]
Redefinition	Technology allows for design of novel learning tasks, previously inconceivable, e.g., students use interactive simulations to explore the movement of tectonic plates and resulting earthquakes.	**Interactive**	Students engage constructively in an equal community of learners, e.g., students explore Avogadro's law, Boyl's law, and Gay-Lussac's law, in groups, (use technology to) document their results (in a shared file) and combine their findings to derive the ideal gas law collaboratively.
Modification	Technology allows for a significant redesign of the task, e.g., the use of a virtual bulletin board to create a multimodal experimental protocol including pictures, videos or audios.	**Constructive**	Students generate new inferences or information, which go beyond the presented materials, e.g., students create their own explanatory videos or e-books to summarize experimental findings in virtual lab reports.
Augmentation	Technology is used as a substitute for traditional media with functional improvement, e.g., students read a text on a tablet computer with embedded hyperlinks to retain more information.	**Active**	Students manipulate (technology enriched) learning materials or activities, e.g., students use the play/pause/zoom function to observe video scenes of a pre-recorded experiment in more detail.
Substitution	Technology is used as a substitute for traditional media with no functional improvement, e.g., students read a plain text on a tablet computer.	**Passive**	Students receive information without showing any indicator of interaction, e.g., they read a scientific text or watch a video.

The SAMR framework by Puentedura [67] describes the quality of technology exploitation in comparison to traditional teaching and learning media on four ascending levels (substitution, augmentation, modification and redefinition; see Table 1, left column) and has been used successfully in various subjects to analyze teachers' abilities to plan and conduct lessons containing technology [62,70]. However, the subject-independent applicability of the SAMR framework, at the same time, limits its usability to adequately describe teachers' underlying content knowledge in one specific subject. Rather, the SAMR framework can be used to describe the relationship and interactions between technology and specific pedagogical practices, particularly how tasks can be enhanced by the use of technology.

The ICAP framework by Chi [68] and Chi and Wylie [69] describes instructional quality in terms of students' cognitive engagement on four descending levels (interactive, constructive, active and passive; see Table 1, right column) and is not limited to materials or activities involving technology. Nevertheless, it can be used to assess students' cognitive engagement achieved through technology exploitation, as conducted, for example, by Deepika et al. [71], Kramer et al. [70] and Wekerle et al. [72].

Chi and Wylie [69] argue that only constructive and interactive cognitive engagement can lead to a deep understanding of subject-specific content. However, as learning materials, activities and objectives vary considerably across subjects, cognitive engagement is inextricably linked to the respective subject or content. Especially science education has very unique ways of thinking and working, which are not common in other subjects. This is reflected in the relationship and interactions between learning objectives in science education and corresponding pedagogical practices.

Considering this, we understand the quality of technology exploitation, as conceptualized by the SAMR framework, as an indicator for (pre-service) science teachers' TPK and students' cognitive engagement with the scientific content via technology, as conceptualized by the ICAP framework, as an indicator for PCK.

In accordance with the current empirical research on the internal structure of TPACK, as discussed in Section 2.1, PCK and TPK are predictors for TPACK, while TCK has no significant influence [4,5,7,8,33]. Accordingly, a combination of distinctive PCK and TPK can be understood as an indicator for high TPACK. Based on this, we combine the SAMR framework [67] as a measure of TPK in action and the ICAP framework [68,69] as a measure of PCK in action, as an alternative to existing TPACK rubrics. This approach has several advantages. Both frameworks are easily applicable to lesson plans or observations and allow for distinguishing possibly varying qualities of multiple technology exploitations in a single lesson, which, in a second step, can be summarized to an overall rating for the respective lesson. Additionally, an approximation of TPACK in action based on the SAMR (for TPK) and ICAP (for PCK) framework is in line with current empirical findings.

2.3. Moderating Factors between TPACK on and TPACK in Action

In order to gain an in-depth understanding of the interplay between TPACK on and in action mixed-method approaches which combine self-assessments with the analysis of related classroom practice are necessary. This implies that inconsistencies between (pre-service) science teachers' TPACK on and in action, as observed in previous studies [25,26], are taken into account and potential moderating factors need to be identified. For example, more recent studies consider, according to the theory of planned behavior (ToPB; [18]), that the intention to perform a specific behavior depends on one's attitudes toward the behavior, subjective norms and perceived behavioral control [20,23–25]. Attitudes toward a specific behavior can either be positive or negative. Subjective norms refer to social norms or pressure, such as colleagues' or superiors' opinions toward the behavior. Perceived behavioral control describes the availability of resources as well as one's self-efficacy toward the behavior.

Related to the use of technology in (science) education, Ertmer and Ottenbreit-Leftwich [73] identified four factors that positively influence (pre-service) teachers' intentions to integrate technology into practice: knowledge, self-efficacy and pedagogical beliefs, as well as subject and school culture. While knowledge refers to teachers' TPACK on action [73], the remaining three factors can be located in the theory of planned behavior. The authors of [21] argue that subject and school culture determine corresponding subjective norms on the expected use of technology in the respective context (subject/school), that pedagogical beliefs are expressed by teachers' attitudes toward the use of technology and that self-efficacy (in combination with constraints) forms the perceived behavioral control. Therefore, all factors influencing teachers' intentions toward the use of technology in education and, ultimately, practice, as identified by Ertmer and Ottenbreit-Leftwich [73], can be related to the ToPB.

Also, several other authors have outlined the relationship between TPACK and ToPB, such that ToPB is a valid framework to study (pre-service) teachers' behavioral orientations toward the use of technology in practice [19,20,25]. However, studies rarely go beyond teachers' planned behavior and relate TPACK on action to their actual classroom practice. Studies investigating teachers' TPACK in action by lesson plans or observations only occasionally address TPACK on action or moderating behavioral orientations [35,48,74–76]. To gain an in-depth understanding of the interplay between pre-service teachers' professional knowledge, intentions, and resulting actions in practice studies, combining various methods, are necessary.

3. Context of the Study

Universities face the challenge of integrating technology into their teacher education programs without omitting other essential content. One possible solution is to offer (elective) add-on modules, which supplement the existing study program by focusing on the use of technology in a class or lab [3]. However, this leads to an additional workload for pre-service teachers, which cannot always be credited. Consequently, these modules are often attended by just a few participants, and in the case of elective modules, pre-service teachers have to make a choice between different courses. One way or another, only some pre-service science teachers can attend and benefit from add-ons addressing technology in science education. However, as we believe that it is crucial that all pre-service teachers develop the necessary knowledge to enhance students' scientific literacy through technology, we decided to implement technology into modules that are mandatory for all pre-service science teachers. There are two main reasons for this: First, we can assure that all pre-service science teachers graduating from Leuphana University will have attended the modules. Secondly, following the transformative view of TPACK, we want to link the development of PCK and, building on this, TPACK among pre-service teachers more closely. Therefore, teaching and learning technology was implemented systematically into the existing science education modules in the form of *digital supplements* and *digital reminders*, as described in the following section. Up to then, science education modules focused "merely" on pre-service teachers' PCK development.

Module Design

The study is embedded in the three-year (six semesters) bachelor's program at the Leuphana University. A special feature of the science teacher education program at Leuphana University is that pre-service primary and secondary science teachers jointly attend the science education modules 'Teaching and Learning Science' and 'Science in Everyday life' in the fourth and fifth semesters of the bachelor's program. First, pre-service teachers attend the mandatory module 'Teaching and Learning Science', followed by 'Science in Everyday Life', consisting of a lecture and a complementary seminar in each. Each module consists of about 13 weeks, with 2 h each lecture and seminar. In the first module, fundamental science education topics are discussed in theory and complemented by digital supplements (app. 15–20 min of each lecture), which include exploitation possibilities of technology in class related to the respective topic (see Table 2). In the complementary seminar, pre-service teachers additionally learn to design diagnostic tasks with quiz apps, create short explanatory videos on science topics and use simulations and remote labs as well as digital measuring sensors.

Table 2. Content and digital supplements of the module 'Teaching and Learning Science'.

Session	Content	Digital Supplement with Practical Deepening/Application in the Complementary Seminar
1	Introduction	Pre-test
2	Digital media	Glossary: digital media for science education
3	Inclusion	Universal design for learning in digital media and assistive operating aids
4	Diagnostics	Quiz apps
5	Differentiation	QR tip cards
6	Materials and tasks	E-books and learning apps
7	Language	Multimodal design of interactive work sheets
8	Explanations	Explanatory videos
9	Nature of science	Nature of science in society [77]
10	Models	Modeling software and virtual and augmented reality
11	Students' beliefs	Concept cartoons, mind maps and concept maps
12	Experiments	Internal and external sensors, interactive simulations and remote labs
13	Feedback and assessment	Classroom/student response systems

The subsequent module 'Science in Everyday Life! focuses on the practical design, teaching and reflection of science lessons. Additionally, digital reminders (brief, explicit verbal and/or written reference to the potential use of certain tools for a specific purpose) relating to the digital supplements from the previous module are incorporated through the lecture to demonstrate how technology can be implemented and support science teaching and learning in manifold ways. In the complementary seminar, students deepen their theoretical knowledge in practice by designing a technology-enhanced lesson. In groups of three to four, they present this lesson to the other participants of the seminar by teaching selected parts of the unit and providing an overview of the remaining lesson.

4. The Study: Aims and Research Questions

The aim of the study is to implement technology following the transformative view of TPACK [2,4–8,35–38] into the science education program at Leuphana University in order to increase pre-service teachers' professional knowledge, particularly TPACK on and in action, as well as to positively influence their behavioral orientations toward the use of technology (according to ToPB). The study design presented here is a novelty, as the development of TPACK on action, ToPB and TPACK in action are explicitly linked to each other and captured using a mixed-methods approach. In addition, the findings contribute to a better understanding of the impact of integrating technology into existing modules (which focus on PCK) in tertiary science teacher education and are, therefore, useful for redesigning curricula at other universities in the future.

This leads to the following research questions:

1. How do pre-service science teachers' self-reported professional knowledge, particularly TPACK, and their behavioral orientations develop during the modules?
2. How distinctive are technology exploitations in pre-service science teachers' lesson plans in terms of quantity and quality after attending the modules?
3. How do pre-service science teachers rate the quality of the redesigned modules?

5. Methods

This section is divided into a characterization of the sample (see Section 5.1), followed by a detailed description of the data collection process and used instruments. We combine measures (by questionnaire) of self-rated TPACK on action and ToPB (see Section 5.2.1) with TPACK in action derived from lesson plans (see Section 5.2.2) to obtain an in-depth understanding of pre-service science teachers' TPACK development. This approach has three advantages: first, the whole decision-making process for the integration of technology, from underlying TPACK on action and moderating behavioral orientations to resulting TPACK in action, is captured; second, it allows for combining the advantages of various TPACK on/in action measurements (questionnaire/analysis of lesson plans) while compensating limitations; and third, it allows for a higher resolution in terms of individual technology exploitation in practice.

5.1. Participants

In total, the sample consisted of 133 participants separated into 2 cohorts, 74 pre-service teachers in the first year and 59 in the second (Table 3). Sample sizes decreased in-between measurement points (pre/re/post) from 102 down to 55 students. This high dropout rate was due, among other things, to the fact that the pre- and post-tests were two semesters apart. Some students did not attend modules in directly consecutive semesters, and others did not pass the exam in module 'Teaching and Learning Science', which was why they did not attend the following module. The study design and data collection process were identical for both cohorts.

Table 3. Sample of this study.

N **(Pre/Re/Post)**	**133** **(102/76/55)**				
Gender (%)	**Male** 12.0	**Female** 64.7	**Diverse** 0.0	**No answer** 23.3	
Age (years)	**M** 23.4	**SD** 4.68			
Subjects (%)	**Science (primary)** 34.6	**Biology (2nd)** 35.3	**Chemistry (2nd)** 12.8	**No answer** 23.3	
Teaching experience (%)	**None** 28.8	**1–10 h** 32.6	**11–30 h** 7.6	**>30 h** 7.6	**No answer** 23.5

5.2. Data Collection

The accompanying research followed a mixed-methods approach. At three measuring points (pre/re/post—before, in-between and after attending the two modules) pre-service science teachers reported their professional knowledge (TPACK on action) and behavioral orientations according to the ToPB through a questionnaire. Lesson plans were analyzed by qualitative content analysis [78] in terms of quantity and quality of technology exploitation as well as pre-service teachers underlying TPACK in action. Additionally, the quality of the modules was assessed through the standardized teaching evaluation form (TEF) of the Leuphana University, supplemented by module-specific items. The study design and accompanying data collection are presented in Figure 2.

Due to the preservation of anonymity and the design of technology-enhanced lessons by groups of three to four pre-service science teachers, it was not possible to combine the quantitative and qualitative data for individual participants. Nevertheless, the analyzed lesson plans serve as authentic data sources, which supplement pre-service science teachers' self-reported TPACK on action and help to gain an in-depth understanding of pre-service science teachers' TPACK on and in action after attending the modules.

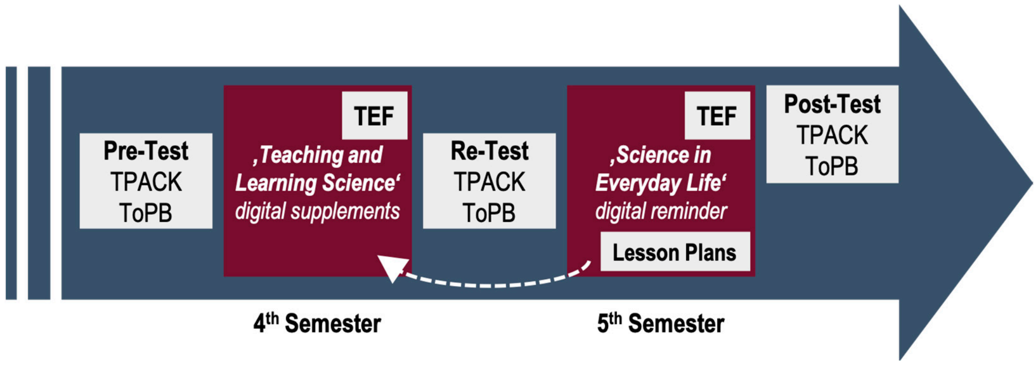

Figure 2. Design of the study and data collection.

5.2.1. Questionnaire

At three measuring points (pre/re/post) students' TPACK on action as well as their behavioral orientations toward the use of digital media in science education according to the ToPB were captured by self-reports. All items were rated on a 5-point Likert scale (from 1 = "strongly disagree" to 5 = "strongly agree").

Pre-service science teachers' behavioral orientations were assessed by an established test instrument, which has been extensively reviewed by the authors with regard to validity and reliability [21]. It consists of five scales addressing attitudes toward the use of technology in science education (eight items, $\alpha = 0.88$), perceived behavioral control (seven items for self-efficacy, $\alpha = 0.73$, and four items addressing constraints, $\alpha = 0.69$), subjective norm (four items, $\alpha = 0.58$) and motivational orientation (six items, $\alpha = 0.87$) as a measure for the resulting intention to use technology in practice [21]. Sample items for each scale are shown in Table 4.

Table 4. Sample items for self-rated TPACK on action and behavioral orientations toward the use of technology in science education.

Scale	Sample Item
Attitudes	With technology, I can plan and adapt science lessons more appropriately for my students.
Subjective Norms	The science curriculum requires the use of technology.
Constraints	The long preparation time often prevents me from using technology in my science lessons.
Self-Efficacy	I can use technology to get feedback from my students on science lessons.
Motivational Orientation	I enjoy thinking about how to use technology in the science classroom.
CK	I have sufficient knowledge about my science subject.
PK	I am able to stretch my students' thinking by creating challenging tasks for them.
TK	I have the technical skills to use technology effectively.
PCK	I can help my students to understand my science subject in various ways.
TCK	I can use software that is created specifically for my science subject.
TPK	I am able to use technology to introduce my students to real-world scenarios.
TPACK	I can formulate in-depth discussion topics about my science subject and facilitate students' online collaboration with appropriate technology.

Within the scope of the development of a TPACK instrument, in the first step, various national and international TPACK instruments were reviewed. Review criteria were that all seven TPACK dimensions are covered by the instrument, that the number of items per TPACK dimension should be comparable and relatively low (due to the study design, completing the questionnaire should take a maximum of 15 min) while good scale reliabilities are ensured. Only the TPACK instrument by Chai et al. [45] fulfilled all of the given criteria. In the second step, the original items were translated to German and adapted for science teaching. A subsequent review by two experts led to a consensus regarding individual item formulations. A comprehensive overview of all items can be found in [8], and sample items for each scale are shown in Table 4. Evidence of reliability is given by internal consistency in terms of Cronbach's α (α_{CK} = 0.80; α_{PK} = 0.87; α_{TK} = 0.80; α_{PCK} = 0.86; α_{TCK} = 0.71; α_{TPK} = 0.78; α_{TPACK} = 0.86) and confirmatory factor analysis (CFA). In CFA results, the model fit indices were acceptable (RMSEA = 0.07) or slightly less than good fit values (CFI = 0.89, TLI = 0.87).

Note that no (language) instrument, which fulfilled all given criteria, existed at the time of the project launch. In the meantime, instruments comparable in terms of validity and reliability to the one herein presented have been developed, for example, by Schmid et al. [7].

5.2.2. Lesson Plans

To assess the use of technology, 31 lesson plans were analyzed [78]. Pre-service teachers were asked to design and teach a technology-enhanced science lesson for a topic of their choice in groups of three to four students. In doing so, they can benefit from collaborating with peers when implementing technology in the classroom for the first time [10]. Lesson plans included the school type, grade, rationales for their topics (e.g., anchoring in the national curriculum of the respective grade), learning goals, scientific background, students' conceptions and use of technology, as well as a tabular display of the chronological lesson outline (instructional activities, educational reasoning, social form and materials and technology use). A detailed template for the lesson plans is available as open educational resource in [79]. All lesson plans were coded independently by two trained coders in terms of quantity and quality of technology exploitation, showing a substantial initial inter-coder reliability of $\kappa = 0.66$ [80]. Quantity of technology exploitation in lesson plans was coded in terms of the type of technology and user (teacher/learner), with quality in accordance with the SAMR and ICAP frameworks [67–69]). If necessary, subsequent consensus finding was conducted [81]. Thus, all technology implementations described in lesson plans could be unambiguously classified.

Technology exploitation was coded multiple times when the same technology was used multiple times during the lesson or by varying users. Types of technologies were aggregated inductively [82] to provide a better overview of the dominant types of technologies used in lesson plans. In accordance with the hierarchical structure of the SAMR and ICAP frameworks, individual technology exploitations in lesson plans were coded with 1 point (SAMR: substitution; ICAP: passive) to 4 points (SAMR: redefinition; ICAP: interactive). Coding rubrics for the quality of technology exploitation in lesson plans are shown in Table 5.

5.2.3. Module Evaluation

The quality of the courses was assessed through the standardized teaching evaluation form (TEF) of Leuphana University, supplemented by module-specific items. Each module was evaluated individually by participants after attending the respective module. Additional items focused either on digital supplements and practical applications of technology in the accompanying seminar or on digital reminders and the planning and teaching of a technology-enhanced science lesson (Table 6). Where possible, analogous item formulations were used. Participants rated all items on a 5-point Likert scale (1 = "strongly disagree" to 5 = "strongly agree").

Table 5. Rubrics for quality of technology use in lesson plans [70].

ICAP framework					
	Interactive	Students engage constructively in an equal community of learners AND Technology as substitute without functional improvement	Students engage constructively in an equal community of learners AND Technology as substitute with functional improvement	Students engage constructively in an equal community of learners AND Technology allows for a significant redesign of the task	Students engage constructively in an equal community of learners AND Technology allows for design of novel learning tasks, previously inconceivable
	Constructive	Students generate new inferences or information, which go beyond the presented materials AND Technology as substitute without functional improvement	Students generate new inferences or information, which go beyond the presented materials AND Technology as substitute with functional improvement	Students generate new inferences or information, which go beyond the presented materials AND Technology allows for a significant redesign of the task	Students generate new inferences or information, which go beyond the presented materials AND Technology allows for design of novel learning tasks, previously inconceivable
	Active	Students manipulate learning materials or activities AND Technology as substitute without functional improvement	Students manipulate learning materials or activities AND Technology as substitute with functional improvement	Students manipulate learning materials or activities AND Technology allows for a significant redesign of the task	Students manipulate learning materials or activities AND Technology allows for design of novel learning tasks, previously inconceivable
	Passive	Students receive information; no indicator of interaction AND Technology as substitute without functional improvement	Students receive information; no indicator of interaction AND Technology as substitute with functional improvement	Students receive information; no indicator of interaction AND Technology allows for a significant redesign of the task	Students receive information; no indicator of interaction AND Technology allows for design of novel learning tasks, previously inconceivable
		Substitution	**Augmentation**	**Modification**	**Redefinition**
		SAMR framework			

Table 6. Extract from standardized teaching evaluation form (TEF) of the modules. Only course-specific items addressing digital supplements/reminders and practical application of technology are presented.

	Module 'Teaching and Learning Science' incl. Digital Supplements	**Module 'Science in Everyday Life' incl. Digital Reminders**
1	The number of technologies presented in the digital supplements was sufficient.	-
2	The digital supplements were sufficiently focused on science education.	-
3	The seminar offers me sufficient opportunities to deepen my knowledge on technology exploitation into practice.	Planning and teaching an IBL lesson offers me sufficient opportunities to deepen my knowledge on technology exploitation into practice.
4	-	The digital reminders helped me to choose technology while planning and teaching a science lesson.
5	-	It was easy for me to choose technology while planning and teaching a science lesson.

Table 6. *Cont.*

	Module 'Teaching and Learning Science' incl. Digital Supplements	Module 'Science in Everyday Life' incl. Digital Reminders
6	Technology exploitation (as presented in the digital supplements) can be implemented into school practice.	Technology exploitation (as presented in the digital reminders) can be implemented into school practice.
7	Technology exploitation (as presented in the digital supplements) enhances the quality of science teaching and learning.	Technology exploitation (as presented in the digital reminders) enhances the quality of science lessons.
8	Through the digital supplements, I was able to expand my professional knowledge in the area of technology exploitation.	By planning and teaching a science lesson, I was able to expand my professional knowledge in the area of technology exploitation.

The TEFs were organized by Leuphana University as an online questionnaire, which was sent to all pre-service science teachers enrolled in the module at the end of each semester. Participation was voluntary and completely anonymous. Therefore, conclusions about individual participants are not possible. Nevertheless, the TEF gave participants the opportunity to assess the quality of the modules independently of their own participation in the accompanying research. In total, 50 of the participants gave feedback to the first module 'Teching and Learning Science' and 24 to the second module 'Science in Everyday Life'.

6. Results

The results are presented in three parts according to the research questions.

6.1. Development of TPACK on Action and Behavioral Orientations (ToPB)

6.1.1. TPACK on Action Development

The development of pre-service teachers' professional knowledge before, during and after attending the modules is summarized in Table 7 and Figure 3. Comparisons between pre- and re-test and re- and post-test, as well as pre- and post-test, were conducted by paired *t*-tests or Wilcoxon test, depending on the respective data distribution.

Table 7. Self-rated TPACK on action before, during and after attending the course and comparison of first and second, second and third, as well as first and third measurement points (last row), respectively. Abbreviations in order of appearance: number *N*, mean *M*, standard deviation *SD*, *t*-value *t*, *p*-value *p*, effect size *d*, *z*-value *z*, correlation coefficient *r*, and degrees of freedom *df*.

		N	*M*	*SD*	***t*-Test**			**Wilcoxon Test**			
					t	***p***	***d***	***z***	***p***	***r***	***df***
CK	Pre	102	3.47	0.70							
	Re	76	3.56	0.67				3.02	0.003	0.42	50
	Post	55	3.95	0.52	−2.39	0.022	0.37				40
								4.20	<0.001	0.63	45
PK	Pre	102	3.53	0.73							
	Re	76	3.68	0.61				2.73	0.006	0.38	50
	Post	55	3.94	0.58				3.69	<0.001	0.58	40
								5.05	<0.001	0.75	45
TK	Pre	102	3.29	0.82							
	Re	76	3.30	0.79				2.02	0.043	0.28	50
	Post	55	3.77	0.59				3.10	0.002	0.48	40
								4.92	<0.001	0.73	45

Table 7. *Cont.*

		N	*M*	*SD*	*t*-Test			Wilcoxon Test			
					t	*p*	*d*	*z*	*p*	*r*	*df*
	Pre	102	3.43	0.67							
PCK	Re	76	3.71	0.58				4.92	<0.001	0.69	50
	Post	55	4.03	0.53				3.48	<0.001	0.54	40
								5.01	<0.001	0.76	45
	pre	102	3.22	0.68							
TCK	re	76	3.49	0.62				2.48	0.013	0.35	50
	post	54	3.91	0.57				3.49	<0.001	0.55	40
								5.19	<0.001	0.77	45
	Pre	102	3.69	0.72							
TPK	Re	76	3.71	0.58				1.19	0.235	0.17	50
	Post	55	4.24	0.56				4.44	<0.001	0.69	40
								4.30	<0.001	0.64	45
	Pre	101	3.20	0.84							
TPACK	Re	76	3.43	0.60				2.43	0.015	0.34	49
	Post	55	3.96	0.52				3.92	<0.001	0.61	40
								5.29	<0.001	0.80	44

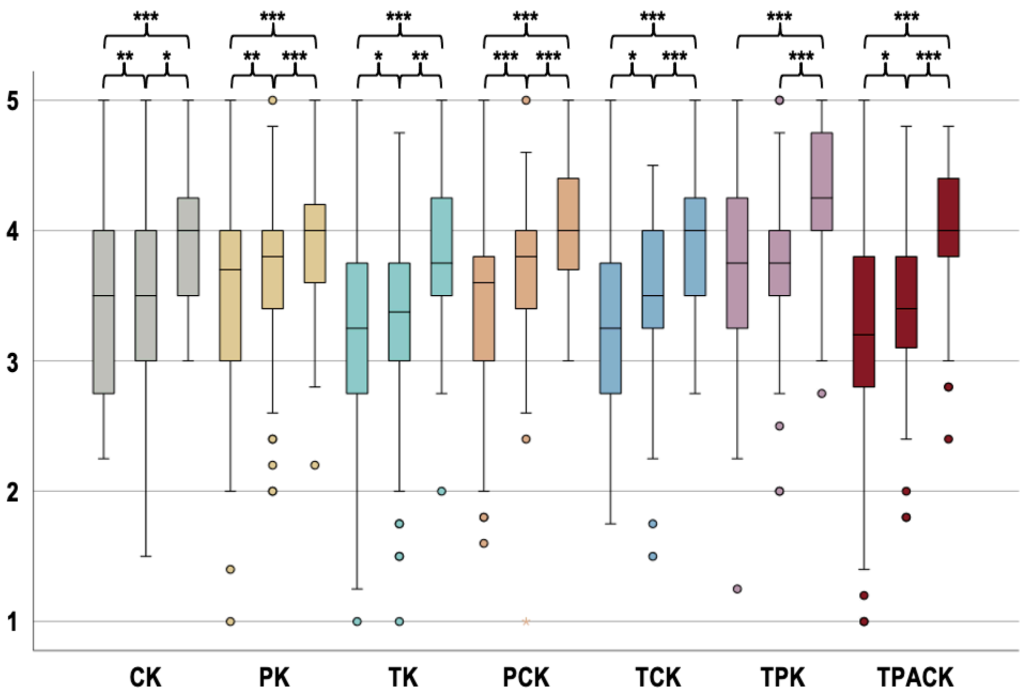

Figure 3. TPACK on action development for pre-, re- and post-test. Significant differences are marked with asterisks (*: $p < 0.050$; **: $p < 0.010$; ***: $p < 0.001$).

The results show that both modules have a positive influence on pre-service science teachers' self-reported TPACK on action with moderate to large effect sizes (Table 7). Especially during the second module, where participants deepen their theoretical knowledge in practice by designing and teaching a technology-enhanced science lesson, a significant change in their self-reported TPACK on action can be observed. Therefore, by adding digital supplements and digital reminders, as well as giving pre-service science teachers the opportunity to apply their knowledge in practice, existing modules focusing on the PCK development can be successfully extended in order to foster pre-service science teachers' TPACK on action.

6.1.2. Development of Behavioral Orientations (ToPB)

As TPACK is addressed explicitly in the modules, pre-service teachers gain positive experiences with technology, which presumably influence their behavioral orientations toward the use of technology in science education as well [14–16]. In accordance with the ToPB, pre-service science teachers' behavioral orientations were captured before, during and after attending the modules (Table 8; Figure 4). High values indicate strong manifestations of the respective variable, for example, a positive attitude toward the use of technology in science education, a strongly perceived norm to use it, severe constraints in using it, a high self-efficacy expectation in using it and a strong motivational orientation to using it in practice.

Table 8. Self-rated behavioral orientations according to the ToPB before, during and after attending the course and comparison of first and second, second and third, as well as first and third, measurement points (last row), respectively. Abbreviations in order of appearance: number, *N*; mean, *M*; standard deviation, *SD*; *t*-value, *t*; *p*-value, *p*; effect size, *d*; *z*-value, *z*; correlation coefficient, *r*; and degrees of freedom, *df*.

		N	*M*	*SD*	*t*-Test			Wilcoxon Test			
					t	*p*	*d*	*z*	*p*	*r*	*df*
Attitudes	Pre	102	3.69	0.66							
	Re	76	3.84	0.57				1.42	0.154	0.20	50
	Post	55	4.15	0.58				3.77	<0.001	0.59	40
								3.54	<0.001	0.53	45
Subjective Norms	Pre	102	3.43	0.61							
	Re	76	3.41	0.47				−0.27	0.790	0.04	50
	Post	55	3.66	0.59				2.06	0.039	0.32	40
								1.59	0.113	0.24	45
Constraints	Pre	102	2.93	0.74							
	Re	76	3.03	0.71				0.41	0.684	0.06	50
	Post	55	2.51	0.70				−3.70	<0.001	0.58	40
								−3.04	0.002	0.45	45
Self-efficacy	Pre	102	2.69	0.65							
	Re	76	3.02	0.57	−5.18	<0.001	0.73				
	Post	55	3.31	0.50	−3.06	0.004	0.48				
					−9.13	<0.001	1.36				45
Motivational Orientation	Pre	102	3.27	0.80							
	Re	76	3.27	0.75	−1.16	0.252	0.16				50
	Post	54	3.66	0.72				2.43	0.015	0.38	40
								3.52	<0.001	0.52	45

Comparisons between measuring points were conducted by paired *t*-tests or Wilcoxon tests, depending on the respective data distribution.

As can be seen from Table 8, pre-service science teachers already had positive attitudes (M = 3.69; SD = 0.66) and motivational orientations (M = 3.27; SD = 0.80) toward the use of technology in science education before participating in the study. In contrast, their self-efficacy was rather low (M = 2.69; SD = 0.65). Over the course of the study, attitudes, self-efficacy and motivational orientations increased consistently, leading to significant differences between pre- and post-test, as shown in Table 8 and Figure 4. Simultaneously, participants' constraints decreased over the course of the study, leading to significant differences between pre- and post-test. No significant differences occurred for subjective norms between the beginning and the end of the study.

Again, effect sizes are bigger between re- and post-test compared to pre- and re-test, with the exception of self-efficacy. This highlights the relevance of incorporating practical experiences in study programs in order to foster not only pre-service science teachers'

TPACK on action but also their behavioral orientations toward the use of technology in science education.

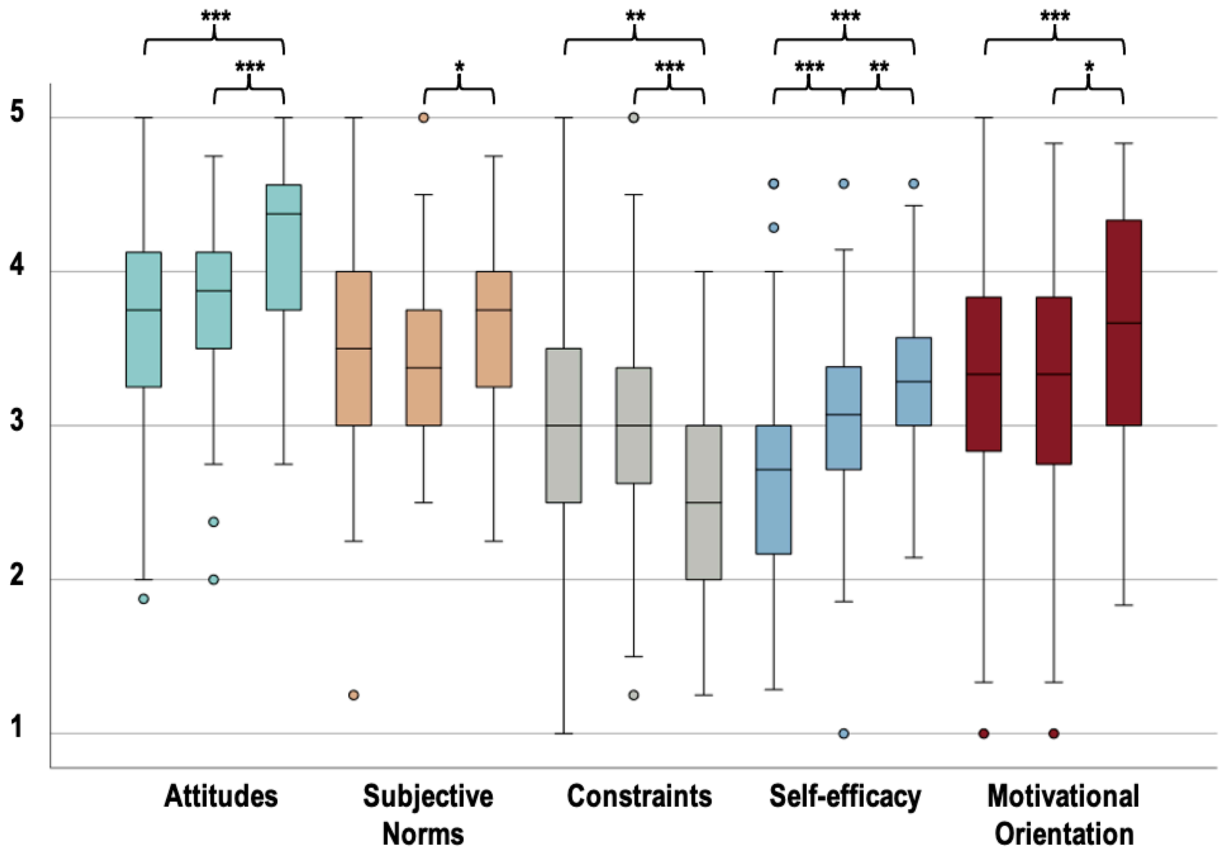

Figure 4. Boxplots for pre-, re- and post-test. Significant differences are marked with asterisks (*: $p < 0.050$; **: $p < 0.010$; ***: $p < 0.001$).

6.1.3. Correlations between TPACK on Action and ToPB Components

Assuming TPACK on action as a predictor for pre-service science teachers' behavioral orientations, positive (negative for constraints) correlations between TPACK on action and ToPB components were expected and verified by the data. Low significant correlations exist between participants' self-rated TPACK on action and their attitudes ($r(129) = 0.261$, $p < 0.01$), moderate between participants' self-rated TPACK on action and their motivational orientation ($r(129) = 0.354$, $p < 0.01$) and high significant (negative) correlations between participants' self-rated TPACK on action and their perceived constraints ($r(129) = -0.551$, $p < 0.01$) as well as their self-efficacy ($r(129) = -0.561$, $p < 0.01$).

6.2. Technology Exploitation in Lesson Plans

Lesson plans were analyzed in terms of quantity and quality of technology exploitation according to the SAMR and ICAP frameworks. Based on this, pre-service science teachers' TPACK in action was derived subsequently and compared to their self-rated TPACK on action.

6.2.1. Quantity and Quality of Technology Exploitation

Overall, participants described 183 technology exploitations in lesson plans ($N = 31$), ranging from 2 to 14 per lesson plan. In 31%, technology was used by teachers (pre-service teachers), in 66% by students (fictional learning group) and in 3% of cases, no information was given about the user. An overview of technology exploitation in lesson plans distinguished by the type of technology and user is shown in Table 9.

Table 9. Quantity of technology exploitation in lesson plans distinguished by type of technology, and user.

Technology Type	User = Teacher	User = Students	User = Unknown	Total
Virtual Bulletin Boards	16	38	1	55
(Explanatory) Videos	16	8	0	24
Presentation Soft- and Hardware	11	9	3	23
Office Applications (Text and Spreadsheet)	4	15	2	21
Response Systems and Quiz Apps	6	12	1	19
QR Tip Cards	0	11	0	11
Graphic Soft- and Hardware	0	8	0	8
eBooks	0	7	0	7
Virtual Reality Applications	1	5	0	6
Measurement Acquisition	0	4	0	4
Other	2	3	0	5
TOTAL	56	120	7	183

Figure 5 shows the quality of these cases of technology exploitation as assessed based on conceptualizations by Puentedura [67] for the level of technology integration (SAMR) and by Chi and Wylie [69] for the cognitive engagement of students (ICAP). Based on the lesson plans, 139 of the 183 cases of technology exploitation could be unambiguously assigned to the SAMR and ICAP frameworks according to the rubrics shown in Table 5.

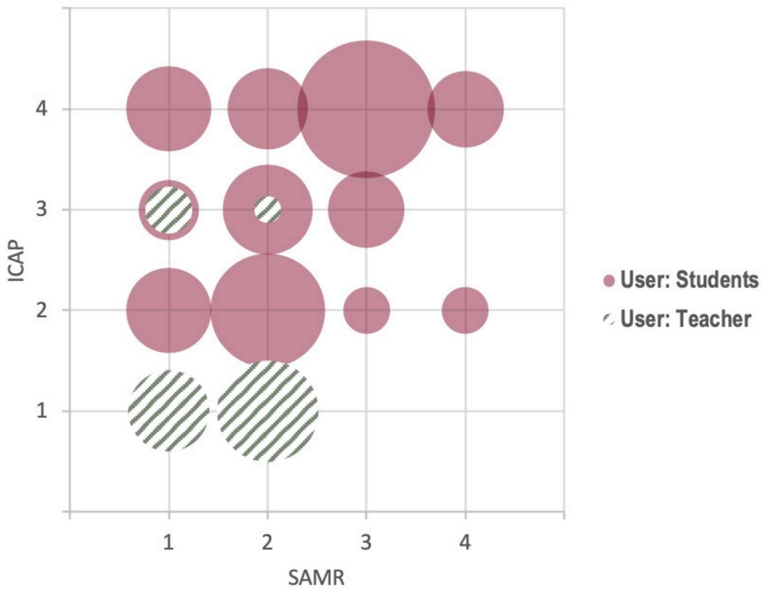

Figure 5. Quality of technology exploitation related based on the SAMR and ICAP frameworks. The size of the respective bubble indicates the number of categorized technology exploitations for each combination of SAMR and ICAP, ranging from 1 to 26 scenarios.

The observed technology exploitation in science lessons follows a typical pattern: First, the respective topic and research question are presented by the (pre-service) science teacher with the help of presentation soft- and hardware, whereby technology is used as a substitute (with functional improvement) for traditional media, leading to a predominantly passive cognitive engagement. The following collection of hypotheses on a virtual bulletin board or with response systems varies across all levels according to the SAMR framework, addressing higher levels of cognitive engagement, namely, constructive and interactive. During the experimental phase, students (in the course of the seminar embodied by other pre-service teachers) are asked to plan and conduct their own experiments. Both real-world experiments including digital measurement acquisition as well as the use of interactive simulations and experimental videos take place. Typically, related documentation is created on virtual bulletin boards or with various office applications. During this phase, technology is almost entirely used by students. When testing their hypotheses, students mostly work in groups, which fosters interactive cognitive engagement with the subject-specific content, while in most lesson plans, technology is used as a substitute for functional improvements or allows for a significant redesign of the task. Additionally, several technology-enhanced scaffolding offers are provided, such as explanatory videos or QR tip cards, leading to online resources with additional information, which students are free to use. For the presentation of results, students use mainly the same technology as for documentation. Thus, students' cognitive engagement decreases from interactive to constructive or passive, depending on the amount of control by the teacher, while the technology use in terms of the SAMR framework is quite similar to the previous phase.

Overall, the quality of technology exploitation and students' cognitive engagement is higher when students are the actual users of technology.

6.2.2. TPACK in Action Derived from Lesson Plans

To assess pre-service teachers' TPACK in action after attending the course, arithmetic means and standard deviations for the quality of technology exploitation in terms of the SAMR and ICAP frameworks were calculated for the observed technology exploitation in each lesson plan. Since SAMR and ICAP values are, by definition, in a range of 1 to 4, no extreme outliers were expected. The arithmetic mean is more sensitive to variation within this data range than other measures and, therefore, can more accurately capture the varying quality of technology use within a lesson plan. The results for each of the 31 groups of pre-service science teachers are presented in Figure 6.

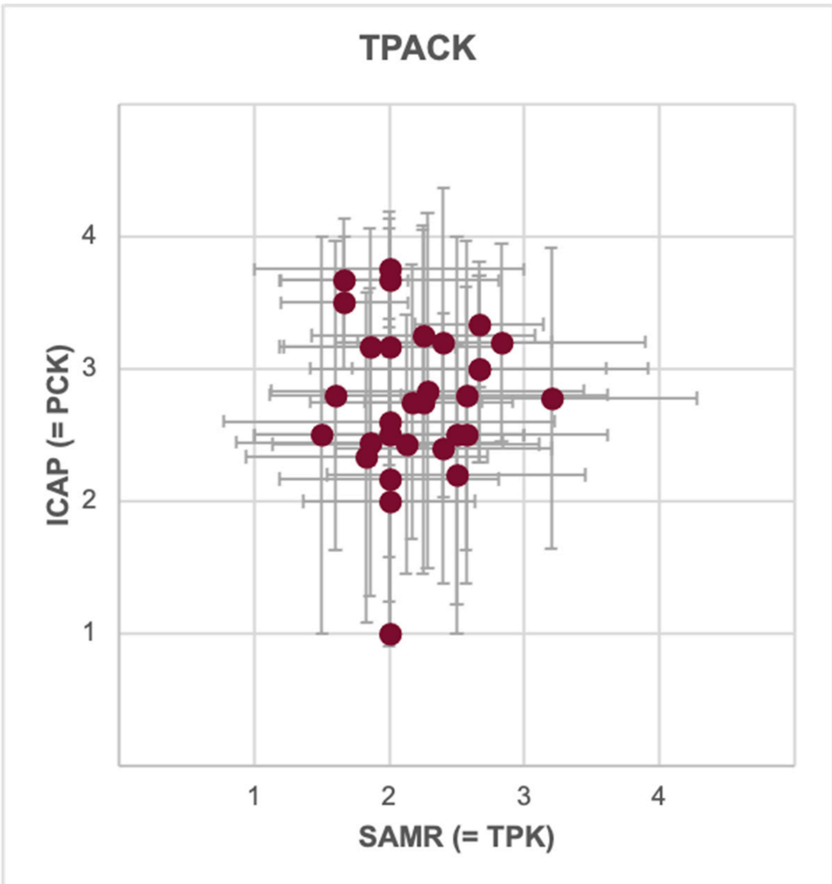

Figure 6. TPACK in action ($M \pm SD$) derived by lesson plans for each group. Combinations indicating low TPACK levels are located in the lower left, high levels in the upper right corner.

Overall, the quality of technology exploitation can be categorized as augmentation ($M = 2.19$; $SD = 0.80$), while students' corresponding cognitive engagement is mainly constructive ($M = 2.78; SD = 0.95$).

Converting these results to a five-point scale, TPACK in action derived from lesson plans can be compared to pre-service teachers' self-rated TPACK on action after participating in the course (Table 10). Note that due to the preservation of anonymity and the design of technology-enhanced lessons by groups of three to four pre-service teachers, it is not possible to combine the quantitative and qualitative data for individual participants. Nevertheless, the data help to gain an understanding of the interplay of pre-service teachers' TPACK on action and their resulting TPACK in action.

Table 10. Comparison of pre-service teachers' self-rated TPACK on action and TPACK in action derived from lesson plans after attending both modules. TPACK in action is approximated by the arithmetic mean of TPK and PCK for each coded technology exploitation.

	On Action (Questionnaire, 5-Point Likert Scale)			In Action (Lesson Plans, Converted to 5-Point Scale)			
	N	***M***	***SD***	***N***	***M***	***SD***	**Δ*M***
PCK	55	4.03	0.53	31	3.48	1.19	0.55
TPK	55	4.24	0.56	31	2.74	1.00	1.50
TPACK	55	3.96	0.52	31	3.11	1.10	0.85

After attending the course, pre-service teachers' TPK, PCK and resulting TPACK in action were consistently lower than corresponding self-rated TPACK on action. Mann–Whitney tests show that these differences are significant for TPK and TPACK ($\text{TPK}: U = 117.5, Z = -6.64, p < 0.001$; $\text{TPACK}: U = 475.0, Z = -3.40, p < 0.001$), while no significant differences in pre-service teachers' PCK on and in action were identified ($\text{PCK}: U = 668.5, Z = -1.66, p = 0.097$).

The comparably lower TPK in action (and resulting TPACK in action) can have several reasons, e.g., pre-service science teachers overestimate their TPK on action, their behavioral orientations limit technology exploitation in practice, they make a reasoned choice against the use of technology (which cannot be derived from lesson plans) or the comparison of varying samples in terms of number and composition.

6.3. Pre-Service Teachers' Assessment of the Course Design

The results of the course-specific TEF items are shown in Figure 7 for the module 'Teaching and Learning Sciene' (left) and 'Science in Everyday Life' (right). Analogously formulated items are presented next to each other.

Pre-service science teachers assessed the number of incorporated technologies in digital supplements (item X.1) as well as their fit to science education (item X.2) as good to very good (number: $M = 4.52$, $SD = 0.71$; fit: $M = 4.35$, $SD = 0.85$). Practical applications of technology in the seminar (item X.3) as well as planning and teaching a technology-enhanced lesson (item Y.3) were rated as good opportunities to deepen theoretical knowledge in practice (seminar: $M = 4.16$, $SD = 0.86$; technology-enhanced lesson: $M = 4.13$, $SD = 0.90$). In addition, participants agreed that technology exploitation (as presented in the digital supplements/reminders) can be implemented into school practice (item X.6: $M = 3.88$, $SD = 1.05$; item Y.6: $M = 4.08$, $SD = 0.91$) and enhances the quality of science teaching and learning (item X.7: $M = 4.02$, $SD = 0.96$; item Y.7: $M = 4.38$, $SD = 0.75$). Overall, pre-service teachers stated that the incorporation of digital supplements as well as planning and teaching a technology-enhanced science lesson promoted their professional knowledge (item X.8: $M = 4.06$, $SD = 1.04$; item Y.8: $M = 4.21$, $SD = 0.82$).

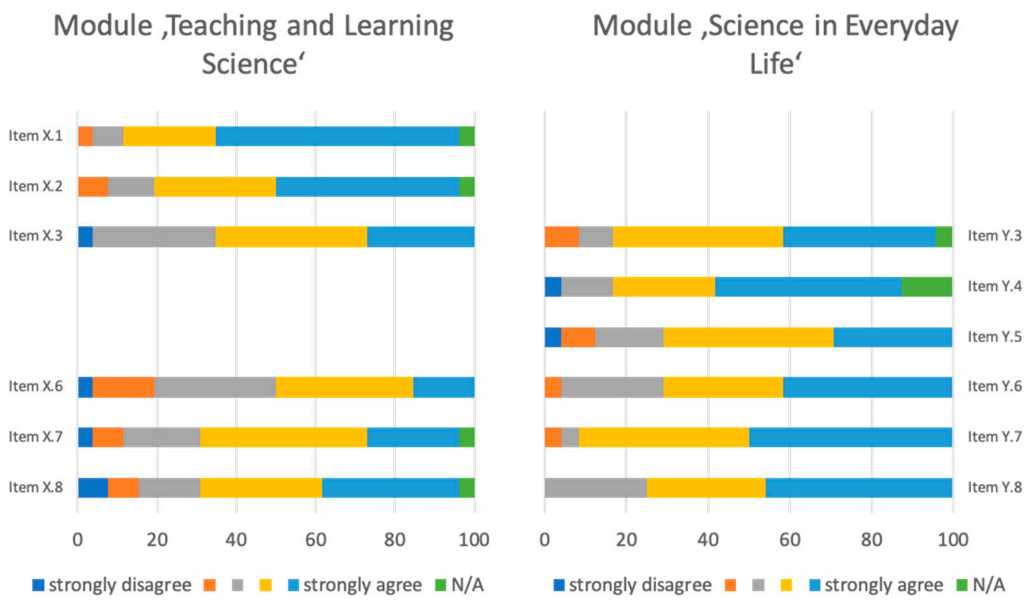

Figure 7. Results from standardized teaching evaluation form (TEF) of the modules 'Teaching and Learning Science' (left, N = 50) and 'Science in Everyday Life' (right, N = 24). Individual item formulations are given in Table 6.

Comparing both modules, the quality of the second module is rated slightly better by the attendees. Participants assessed the quality of the approach, which combines fundamental science education topics (PCK) with technology applications for teaching and learning science (TPACK), as good to very good. In particular, practical deepening in the accompanying seminar and by planning and teaching a technology-enhanced science lesson give pre-service teachers the necessary opportunities to apply and deepen their professional knowledge.

7. Discussion

In the presented study, the transformative view of TPACK [2,4–8,35–38] was used as theoretical background to implement technology systematically into the science teacher education program at the Leuphana University Lüneburg. Participation in the modules led to a significant increase in pre-service teachers' self-reported professional knowledge in all TPACK on action dimensions with moderate to large effect sizes. These findings are in line with other studies examining technology-specific courses [13]. In addition, Zimmermann et al. [14] stated that "[. . .] technology integration courses should not be detached from subject didactics since not only the technology related components of the TPACK framework improved but also PCK" (p. 1868). Thus, courses at the university level should not treat technology as an add-on [10] but rather link the PCK and TPACK development of pre-service science teachers systematically. The presented approach not only fulfills this claim by integrating technology into the existing PCK modules, but it also leads to a significant increase in self-rated PCK and TPACK on action after attending the modules, as evidenced by the data.

TPACK is not only addressed theoretically in the form of digital supplements and reminders, but participants were also given various opportunities to deepen their professional knowledge and apply it to practice, e.g., by designing and teaching a technology-enhanced science lesson.

In accordance with previous studies [14–16], our results show that these positive experiences with technology influence pre-service teachers' behavioral orientations toward the use of technology in science education according to the ToPB [18]. During participation, pre-service teachers' attitudes, self-efficacy and motivational orientations toward the use of technology in science education increased consistently, leading to significant differences between pre- and post-test. Several authors have outlined that the ToPB is a valid framework to study pre-service teachers' behavioral orientations toward the use of technology in practice [19–21,25]. Positive behavioral orientations can be seen as a prerequisite for technology use, with higher values suggesting a greater willingness to integrate technology, which is confirmed by the results of this study. However, to our knowledge, no study combines measures of TPACK on action and behavioral orientations, as well as TPACK in action, to gain an in-depth understanding of pre-service science teachers' TPACK development in the course of a university program. Therefore, the presented study design provides a novelty.

Pre-service science teachers' TPACK in action was derived from lesson plans. In contrast to previous studies that applied TPACK rubrics to lesson plans [31,55,56], TPACK in action was approximated following conceptualizations by Puentedura [67] for the quality of technology exploitation (SAMR) and by Chi [68] and Chi and Wylie [69] for the corresponding instructional quality (ICAP). Commonly, the SAMR as well as the ICAP framework are used to rate the quality of (technology-enhanced) activities/tasks [46,62,70–72,82,83], not teachers' underlying professional knowledge. We argue that the SAMR framework can be applied as a measure of pre-service teachers' TPK in action and the ICAP framework as a measure of PCK in action; thus, the resulting combination of both leads to an approximation of pre-service teachers' TPACK in action. This assumption is in line with current empirical findings on the transformative view of TPACK, which indicate that only TPK and PCK have a significant influence on TPACK [4,5,7,8,33].

Analysis of lesson plans revealed a medium to high quality of technology exploitations (27% substitution, 38% augmentation, 27% modification and 8% redefinition), corresponding instructional quality ranged from passive (17%), overactive (24%) and constructive (20%) to an interactive cognitive engagement (39%) of students. In comparison, the authors of [78] analyzed 85 lessons from experienced biology teachers in terms of quantity and quality of technology exploitation. A total of 71% of technology exploitation was categorized as substitution, 11% as augmentation and 19% could not be clearly assigned to the SAMR framework. The high quality of technology exploitations, as can be seen in the lesson plans, indicates a distinctive TPACK in action after attending the course. Nevertheless, matching the scales reveals that pre-service teachers' TPK, PCK and resulting TPACK in action are consistently lower than corresponding self-assessments, with significant differences for TPK and consequently TPACK as well. While the ICAP framework seems to provide a solid approximation of PCK in action that is consistent with pre-service teachers' self-assessments, it remains to be clarified whether the SAMR framework underestimates TPK in action or if participants overestimate their TPK/TPACK on action. Since TPACK on and in action profiles cannot be matched for individual participants in the present study, it is neither possible to prove nor to disprove both assumptions based on the data. In addition, since pre-service teachers' behavioral orientations toward the use of technology in science education increased in the course of the study, it seems unlikely that differences between their TPK on and in action are caused by intrinsic beliefs. Nevertheless, social desirability in the ToPB data cannot be ruled out since the redesigned modules convey a positive attitude toward technology exploitation in science education. It is needless to say that in digital supplements/reminders, the advantages, as well as possible disadvantages, of technology exploitation were discussed. A further organizational factor that might cause the differences in TPK on and in action is the planning and teaching of a science lesson in groups consisting of pre-service science teachers with possibly varying professional knowledge or behavioral orientations.

Following the transformative view of TPACK, teaching and learning technology was implemented systematically into the existing science education modules at Leuphana University instead of creating additional offers. The quality of the chosen approach was rated positively throughout by pre-service teachers. Participants especially highlighted practical approaches in terms of seminars (module 'Teaching and Learning Science') and the opportunity to plan and teach a science lesson (module 'Science in Everyday Life') where they could apply their newly gained knowledge in practice.

8. Limitations

The presented study has several limitations such as the number of participants or the chosen empirical approach.

The first limitation is the number of pre-service science teachers who attended the course as well as the decreasing participation in the accompanying questionnaire.

Second, due to the design of technology-enhanced lessons by groups of three to four pre-service teachers and the preservation of anonymity in the TEF, it is not possible to combine self-rated TPACK on action with TPACK in action for individual participants or student groups. In addition, the quality of the modules rated by participants cannot be related to the actual development of their professional knowledge through attending the modules.

Third, another limitation of the study is the choice to use the SAMR and ICAP frameworks as measures of TPK and PCK. While this approach is in line with current empirical findings on the transformative view of TPACK, it nevertheless neglects possible influences of TCK and is, thus, only an approximation of pre-service teachers' TPACK in action. Moreover, analyses of lesson plans always fail to identify the reasoned choice against technology, which also is an indicator of a high TPACK on action level.

Fourth, due to economic reasons in the course design and data collection process, pre-service science teachers' TPACK in action was only measured once at the end of the study. An analysis of the TPACK in action development during the course is, thus, not possible.

Some of the above limitations can only be influenced and minimized to a certain extent, while others can serve as a basis for planning future research, as explained in the following section.

9. Conclusions and Implications

Several implications for curriculum designers and future research can be derived from the results presented. The results show that the chosen course design is highly promising. In the sense of "*from PCK to TPACK*", technology should not be taught additionally but systematically integrated into existing science education programs focusing on PCK [8,9]. By doing so, pre-service science teachers can develop the necessary professional knowledge to implement purpose-oriented technology in practice. In addition to the empirically shown increase in pre-service teachers' self-rated TPACK on action and the positive development of their behavioral orientations toward the use of technology in science education during their participation in the presented study, participants rated the quality of the modules as good to very good, highlighting the practical application of technology in the accompanying seminars. Thus, the presented course design can serve as a successful example for curriculum designers to redesign courses at their universities in a similar way.

A first implication for future research is the successful development of a reliable and valid German instrument to assess TPACK on action [8], which did not exist at the time of the project launch.

In addition, the presented study poses a new approach to accessing (pre-service) science teachers' TPACK in action by analyzing lesson plans, which can be easily adapted to lesson observations. In contrast to existing TPACK rubrics, TPACK in action is derived by measures of PCK and TPK according to recent empirical findings on the transformative view of TPACK [4,5,7,8,33]. The SAMR framework by Puentedura [67] is thereby used as an approximation for teachers' TPK. It describes the quality of technology exploitation in comparison to traditional teaching and learning media and has been successfully applied to analyze teachers' abilities to plan and deliver technology-enriched lessons in various (science) subjects [62,70,83,84]. In addition, PCK is measured in terms of students' cognitive engagement achieved through the use of technology according to the ICAP framework [68,69]. Both frameworks allow for a detailed resolution of individual technology exploitation as well as an overall judgment of a lesson. Furthermore, their combination results in a reasoned approximation of teachers' TPACK in action, which takes both teachers'

PCK and TPK, equally into account. Scholars are encouraged to adapt this approach for future research, not only in science education.

Yet, more studies combining measures of TPACK on action, behavioral intentions and TPACK in action are necessary to gain an in-depth understanding of (pre-service) science teachers' TPACK (development). The presented study can serve as an example for the design of future investigations. Nevertheless, due to limitations in the data collection process, measures of TPACK on action and behavioral orientations could not be combined with TPACK in action for individual participants, which is, thus, a future research desideratum.

The presented results as well as previous studies make evident that teachers' self-rated TPACK on action and behavioral intentions are sometimes inconsistent with their actions in the classroom [25,26]. To understand this discrepancy, the analysis of lesson plans or observations needs to be extended, e.g., through interviews that focus on the actual planning process. Exclusively looking at the final product, not all indicators for a high TPACK level, such as the reasoned choice against technology exploitation, can be identified. Therefore, approaches that give teachers the opportunity to explain their choice to (not) implement technology in practice are a further research desideratum.

Last but not least, current research focuses on pre-service science teachers' TPACK development in the course of various study programs. All of these studies (including the presented) assume that participating pre-service science teachers will apply their gained professional knowledge in the future, but the evidence is still missing. Long-term studies that follow pre-service science teachers in their transition from university to school practice are needed to fully understand the impact of university courses that promote pre-service science teachers' TPACK.

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