

Special Issue Reprint

Empowering Teacher Professionalization with Digital Competences

Edited by
Charlott Rubach and Rebecca Lazarides

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Editorial: Empowering Teacher Professionalization with Digital Competencies

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1. Introduction

As digital technologies continue to reshape education, equipping teachers with digital competencies has become a pressing need in both policy and research across Europe and worldwide. Teachers are widely recognized as change agents in shaping and implementing meaningful digital learning experiences in schools (Foster, 2023). Accordingly, international organizations such as the OECD (2023) have emphasized the urgent need to prepare teachers for teaching in technology-supported and digital contexts, and thus, to systematically support their ongoing professional development in this domain.

International empirical findings have highlighted that, while teachers across different countries acknowledge the relevance of their digital competencies, they often report insufficient preparation during their initial teacher education (see Eickelmann et al., 2019; Fraillon et al., 2020; OECD, 2023). In response, various European countries have established initiatives and funding programs aimed at strengthening the digital competencies of teachers—often through stronger connections between research, practice, and policy. In recent years, teacher education institutions across Europe have taken important steps toward integrating digital education into initial teacher education and professional development (see Norhagen et al., 2024; Richter et al., 2024; Rubach & Backfisch, 2024; Tomczyk & Fedeli, 2022). In many countries, the promotion of teachers' digital competencies has now been formally regulated and is increasingly anchored in teacher education curricula as an explicit educational goal (OECD, 2023). Correspondingly, research has increasingly addressed this development by examining topics such as teacher professional development programs for in-service teachers, (extracurricular) learning opportunities in teacher education, and the role of teacher educators and their education (Arstorp et al., 2024; Lazarides et al., 2024; Norhagen et al., 2024). Building on these foundations, research continues to emphasize the importance of understanding how learning opportunities have to be designed in order to influence the development of digital competencies of pre-service and in-service teachers (Norhagen et al., 2024; Rubach & Backfisch, 2024). Research based on (quasi)-experimental interventions suggests, for example, that different goals—whether emphasizing pedagogical integration, technical functionality, or hands-on application—affect the distinct aspects of teachers' digital competence needed for their profession (Ning et al., 2022). Despite the vivid empirical research carried out in this field, it is still an unresolved question whether, how and under which conditions pre-service and in-service teachers benefit from professional development formats that aim to increase their digital competencies.

To address this gap, the present Special Issue provides a platform for experts from both teacher education and teacher professional development who have examined the quality and design of technology-supported learning environments and their impact on pre-service and in-service teachers' digital competencies. In line with research on high-quality teaching, the studies in this Special Issue emphasize both the process dimension, i.e., how instruction is designed, and the product dimension—what is to be learned. By drawing on these findings, we are now in a position to not only conclude that certain formats successfully foster teachers' digital competencies, but also to understand how such learning formats need to be designed in order to be effective. The work presented in this Special Issue informs education research about central preconditions to foster teachers' digital competencies systematically, and also provides knowledge for educational practice about the design principles of teacher education as well as teacher professional development programs.

2. Perspectives on Teacher Professionalism in the Digital Era

The professionalism of educators in the digital era refers to the idea that teachers possess the necessary digital competencies and that they align their behavior with these competencies to effectively navigate and shape digital teaching and learning environments (Krumsvik, 2011; Redecker, 2017). Multiple theories and frameworks provide important insights into competencies that provide grounding for teachers' professional behavior in the digital era (see for an overview Rubach & Lazarides, 2023). In line with these frameworks, we differentiate between basic and professional digital competencies whereby basic digital competencies are the mandatory grounding to develop the full potential of professional digital competence (Rubach, 2024). This developmental perspective suggests that both basic and professional digital competencies form digital competence (see Hämäläinen et al., 2021; Law et al., 2018; Rubach, 2024).

Based on the definition of the general professional competence of teachers by Blömeke and Kaiser (2017), we posit that, transferred to the digital context, the basic digital competence of teachers consists of the knowledge, motivational beliefs and skills and practices required when using technology to analyze and select digital data and information, to communicate and collaborate online and participate in the digital world, to create and share digital content, to perform tasks and solve problems in digital environments or by using technology, to be responsible with privacy, to protect health and the environment and to reflect on and analyze the ongoing digital changes and essential phenomena of technology (Calvani et al., 2008; Ferrari, 2013; Ilomäki et al., 2016). Professional digital competence then builds on these basic digital competencies and consists of the knowledge, motivational beliefs and skills required when using technology “with good pedagogic-didactic judgement and [...] awareness of its implications for learning strategies and the digital Bildung of pupils and students” (Krumsvik, 2011, p. 45). Taking these definitions as the orientation for educating (future) teachers, it becomes clear that the development of digital competencies is a complex and multi-layered endeavor. First, it is essential to address both basic and professional digital competencies in teacher education and training. Second, multiple educational goals are subsumed under this broader objective—namely the promotion of knowledge, motivational beliefs, such as competence-related beliefs, value beliefs, or attitudes, and situation-specific skills (see Lachner et al., 2021; Max et al., 2022; Rubach et al., 2019; Sáez-López et al., 2023). Third, the development of these competencies cannot be limited to a single stage of the professional career path for teachers. Instead, the development of teachers' digital competencies must be conceptualized as a successive, longitudinal and cumulative process that spans initial teacher training, early-career induction, and ongoing professional development, particularly as new technologies and opportunities

for the use of technology in educational settings are constantly emerging. To understand how digital competence can be developed in this longitudinal and cumulative process, it is essential to examine the quality of learning environments.

3. Perspectives on the Quality of Learning Environments to Support Teacher Professionalism in the Digital Era

To effectively support teachers in their professional development—particularly in this digital era—we can draw on insights from instructional quality research. This field emphasizes that high-quality teaching and learning environments are defined by the integration of both a process and product perspective: how (good) learning happens (i.e., the process), and what is (intended to be) learned (i.e., the product) (Reusser & Pauli, 2021; Praetorius & Gräsel, 2021). Understanding how such environments are designed is essential for enabling effective professionalization.

Didactic perspectives on teaching contribute to this understanding by offering conceptual tools with which to analyze and design instruction in a way that systematically aligns learning processes with the intended outcomes. The central assumptions are that effective teaching requires the careful coordination of multiple interrelated components: the content to be taught, the methods of instruction, the learners' prerequisites, and the sociocultural and organizational conditions in which learning takes place (e.g., Heimann et al., 1979; Helmke, 2022). These elements must be considered collectively, as the focus is not merely on the effectiveness of a single method (process) but on how various elements can be integrated to support the intended learning outcomes (product).

In the context of digitalization, two central goals emerge for both pre-service and in-service teachers: teaching with technology and teaching about technology (Eickelmann et al., 2019; Krumsvik, 2011; Rubach, 2024; Redecker, 2017; OECD, 2023). Addressing these goals requires a process-oriented comprehension of how to support the development of digital competencies through carefully constructed instructional settings in teacher education. This, in turn, raises the question of how instructional processes must be structured—a question that integrates didactic elements with a consideration of both content-generic and subject-specific teaching strategies (see Charalambous & Praetorius, 2020). Whereas content-generic standards can be applied to support competence development among all contents and subjects, content-specific standards help identify the design of learning processes necessary for learners to develop an understanding of specific content (Reusser & Pauli, 2021). Charalambous and Praetorius (2020) emphasized the importance of establishing a shared understanding of instructionally meaningful and high-quality learning processes. We adopt this perspective in the present Special Issue and apply it to teacher education—specifically in preparing teachers to use technology effectively and to nurture the digital competencies required for this task.

This reflection is grounded in the MAIN-TEACH model (which is multi-layered and integrated, conceptualizing the quality of teaching, Charalambous & Praetorius, 2020). This model is informed by the German models of opportunities and uses of instruction (see Helmke, 2022). The model emphasizes instructional processes as contributing to student learning only when learning opportunities are not only provided for but also embraced by learners, resulting in meaningful learning activities. The MAIN-TEACH model distinguishes three levels of instructional quality. At the core lies the principle of differentiation and adaptation to learners' needs, which influences all strategies of instructional quality in the second and third layer. The second layer comprises stand-alone quality dimensions such as classroom and time management, socio-emotional support, and support for active engagement. The third layer focuses on instructional quality dimensions that are

intertwined and directly relevant for learning, including four dimensions: “supporting practicing, cognitive activation, formative assessment, and selecting and addressing the content and subject-specific methods” (Charalambous & Praetorius, 2020, p. 5). The MAIN-TEACH model can also serve as a conceptual lens through which to examine how teacher education and teacher professional development programs should be designed to foster digital competencies. It highlights the need to address both generic and content-specific dimensions of teaching when preparing pre-service teachers and in-service teachers to operate within digitalized learning environments. Simultaneously, the integration of generic and content-specific dimensions of teaching requires ongoing reflection from a subject-specific perspective on the following lines of inquiry: to what extent are these dimensions sufficient, how differentiated are they, and where might they need to be expanded (see Praetorius & Gräsel, 2021)? For this purpose, established frameworks such as the SQD model (Synthesis of Qualitative Evidence on the Development of Digital Competence) offer valuable guidance for teacher education and technology use. The SQD model by Tondeur et al. (2012, 2025) outlines teaching principles that can be meaningfully aligned with the third level of the MAIN-TEACH model, particularly in guiding the establishment of learning opportunities in teacher education to support pre-service teachers’ digital competencies. The SQD outlines six key principles to guide the preparation of pre-service teachers for developing digital competence: having role models, being in authentic environments, training on instructional design, being in collaborative settings, receiving feedback and reflecting on experiences. In this Special Issue, we adopt both generic and content-specific perspectives on instructional quality—focusing on the processes through which learning is facilitated and the intended outcomes—to explore fundamental lines of inquiry investigating how instructional quality contributes to the professional development of pre-service and in-service teachers in the digital era.

4. Studies of the Special Issue

This Special Issue focuses on the effectiveness of instructional characteristics and strategies in supporting the professional development of both pre-service and in-service teachers in the context of digital transformation. Five contributions in this Special Issue examine how digital professionalization unfolds in *pre-service teacher education*, with a focus on the development of motivational beliefs and attitudes, knowledge, and skills, as well as ICT use. These studies investigate a range of learning environments, from curricular classes and extracurricular online courses to school-based internships. Through the perspective of research on instructional quality and the MAIN-TEACH model, the scholars included in this Special Issue analyze key characteristics of these learning environments, for example, what is taught (content), how learning is being facilitated (instructional strategies), and what the outcome of learning processes is.

Runge, Hebibi, and Lazarides investigated the role of content in fostering pre-service teachers’ digital competence, specifically by examining opportunities for engaging with artificial intelligence (AI) in teacher education. Using cross-sectional data from 143 pre-service teachers at multiple German universities, the authors indicated that students who participated in courses addressing AI reported stronger AI-related TPCK beliefs (Technological Pedagogical Content Knowledge), perceived AI tools as easier to use and more useful, and demonstrated greater intentions to use AI in future classrooms. Furthermore, higher levels of perceived usefulness were associated with both a greater intention to use AI and more frequent use of AI.

Another key focus is the development of pre-service teachers’ diagnostic skills for identifying students’ cognitive engagement when using technology in the classroom, and

exploring how teacher education can effectively foster such skills. These diagnostic competencies are crucial for meaningful technology integration, as they enable teachers to assess the learning potential and impact of digital tools on students' cognitive processes. *Roeben, Vejvoda, Murböck, Fischer, Schultz-Pernice, Lohr, Stadler, Sailer* and *Heitzmann* examine the use of a simulation-based learning environment which provides an authentic yet simplified setting in which pre-service teachers can practice and develop their diagnostic skills. Drawing on data from 213 pre-service teachers at a German university, the authors validated the simulation tool in a pre–post design. Their findings indicate that the simulation effectively elucidated pre-service teachers' difficulties in accurately determining students' cognitive engagement during ICT-supported instruction.

Hirsch and *Rubach* investigate the instructional strategies implemented in teacher education courses and their longitudinal effects on changes in pre-service teachers' professional digital competence beliefs—specifically, their beliefs regarding technological pedagogical knowledge (TPK) and technological pedagogical content knowledge (TPCK). The authors focus on the instructional strategies outlined in the SQD model (Tondeur et al., 2012), such as providing role models, enabling interactions with teachers and students in schools, fostering peer discussions on digital learning, and offering feedback on digital competence development. Using longitudinal data from 308 pre-service teachers at a German university, the study found that TPK and TPCK beliefs did not develop naturally over the course of a semester. However, competence beliefs became significantly stronger throughout the course of the semester, compared to at the beginning, among students who reported greater satisfaction with the SQD instructional strategies used. Notably, the orchestration of these strategies was critical: it was not the presence of any single strategy, but rather the combined and coordinated use of multiple strategies, that contributed to the development of professional digital competence beliefs in pre-service teachers.

Also focusing on proposed strategies in the SQD model (Tondeur et al., 2012), *Aumann, Grassinger*, and *Weitzel* examine the impact of learning environments constructed in accordance with the SQD model, focusing specifically on internship settings as critical components of teacher education. In their longitudinal study, they investigated how pre-service biology teachers' motivational beliefs changed over the course of a practicum using a pre–post design. The sample consisted of 43 pre-service teachers at a German university. Prior to the internship, students received a theoretical introduction, designed and discussed lesson plans incorporating explanatory videos, and created planned video content in collaboration with their peers. During the practicum, the developed lesson plans—including the use of video-based instruction—were implemented in real classroom settings and subsequently reflected upon. The findings indicate that, following the internship and its associated preparatory and reflective phases, pre-service teachers reported increased self-efficacy and more positive attitudes toward the use of technology in the classroom. In addition, students described a stronger motivational orientation toward integrating technology into their future teaching practices.

Johnson, Schmit, Schneider, Rossa, and *Müller* explore the potential of an extracurricular learning environment designed based on SQD principles (Tondeur et al., 2012). In their longitudinal mixed-methods study, the authors examined the effectiveness of a 10-module online course (total of 90 h) on the development of basic and professional digital competencies. The study involved 40 pre-service teachers from one University in Germany. The training addressed a broad range of topics, including the theoretical foundations of digital teaching, ICT applications, legal frameworks, media didactics, and the use of digital teaching materials. The results showed significant increases in participants' technological knowledge (TK), technological content knowledge (TCK), and related competence

beliefs. However, no significant changes were observed in participants' technological pedagogical content knowledge (TPCK) competence beliefs, ICT-related value beliefs, or professional digital knowledge. In follow-up interviews, participants reflected on their experiences. While they appreciated the collaborative elements and the personalized nature of the training—particularly the individual feedback—some criticized the lack of practical application and reported that the use of videos failed to fulfill the intended role-modeling function.

Three contributions in this Special Issue focus on the *professional development of in-service teachers* and explore how their digital competencies can be strengthened through different learning experiences. One relevant approach to shaping the content that pre-service and in-service teachers engage with is the use of role models. *Amdam, Nagel, Njå* and *Forsström* employ this approach by investigating highly digitalized schools, focusing on how experienced teachers in 1:1 settings have perceived effective teaching. The data they considered came from 1505 Norwegian teachers teaching in elementary school or secondary schools. Two key findings emerged from their study: First, classroom management was identified as a critical factor in 1:1 classes; teachers emphasized the importance of combining strategies—building strong relationships with students, providing clear structures, goals, and rules, and leveraging digital tools for instructional oversight. Second, the study revealed that teachers with lower digital competence focused primarily on the availability of resources and organizational aspects, while those with medium to high competence levels placed greater emphasis on classroom management and instructional practices when using technology.

In addition to the relevant content to be discussed and the appropriate strategies for using technology, the effectiveness of further training for in-service teachers was examined. *Annemann, Menge, and Gerick* investigated in-service teachers' participation in professional development programs related to technologies, and how such participation is associated with teachers' attitudes toward technology, technology usage, and their teaching about technology. Drawing on international cross-sectional data from the international large-scale ICILS study, the authors found that teachers ($N = 10,389$) who engaged in professional development focused on (a) technology applications, (b) the integration of technology into teaching, (c) subject-specific digital resources, (d) the use of technology for student learning, and (e) personalized learning reported more favorable attitudes toward technology. These teachers also reported more frequent integration of technology into their classrooms and placed greater emphasis on fostering students' digital competencies.

Lastly, *Fütterer, Wurst, and Goeze* examined the impact of a professional online development program on their digital competencies in Germany. Specifically, the authors investigated the perceived quality of the online professional development course. They integrated active learning elements with feedback, critical reflection through video vignettes, engagement in professional learning communities, opportunities for the practical implementation of content, and reflecting on teaching experiences. In their study, which had pre–post design, the authors examined the effects of this one-month online program (totaling 18 h) on 76 in-service teachers' self-reported satisfaction, perceived competencies, and knowledge. Results from the pre- and post-assessments indicated that participants perceived the program as meaningful, particularly valuing the interactive components and video-based learning scenarios. However, objective assessments of knowledge and abilities did not show significant changes over time.

5. Summary of Insights on Empowering Teacher Professionalization with Digital Competencies

The contributions in this Special Issue reveal that fostering digital competencies in teacher education and professional development requires coordinated attention to both the processes of learning—that is, what is to be learned—and how instruction can be structured to facilitate learning or professional development. The following sections highlight evidence-based core components of instructional quality that were used to foster digital competencies across studies—components that are reflected in the MAIN-TEACH and SQD models and that are here further differentiated bearing in mind the empirical findings presented in this Special Issue. By synthesizing these findings, this Special Issue contributes to a clearer understanding of what constitutes effective professional learning and proposes concrete directions for the development of research-informed and evidence-based training programs for both pre-service and in-service teachers.

Aligning Curricula with Professional Realities. Since instructional processes are closely aligned with the content being taught, the selection and relevance of digital learning content play a pivotal role in shaping teacher professionalization. This focus directly relates to one of the key instructional quality dimensions identified in the MAIN-TEACH model—*selecting and addressing the content*—which emphasizes that the choice, clarity, and contextual relevance of content are central to enabling meaningful learning processes. The findings in this Special Issue underscore the importance of integrating domain-specific digital content into teacher education and professional development—ranging from various available ICTs, AI, the pedagogical use of ICT or the legal aspects of ICT use (see Runge et al., 2025; Fütterer et al., 2025; Annemann et al., 2025). This content and the curriculum of teacher education should, as suggested by the authors, be continuously updated to reflect technological developments, emphasizing the need for lifelong professional learning (Amdam et al., 2024; Johnson et al., 2024).

Designing authentic learning environments. In addition to the selection and integration of relevant content, a key consideration is the design of learning environments that are pedagogically authentic—that is, environments that are meaningful and realistic from the perspective of (future) teachers (Tondeur et al., 2012). Scholars in this Special Issue have addressed authenticity by using simulations that allow students to develop their skills in lifelike scenarios without real-world consequences (Roeben et al., 2025), as well as by providing opportunities to practice the use of technology in actual classroom settings, such as through internships (Aumann et al., 2025; Fütterer et al., 2025; Hirsch & Rubach, 2024).

Connecting Theory, Empirical Evidence and Practice. The importance of connecting theory and practice emerges as a core factor to support pre-service and in-service teachers (see Tondeur et al., 2012). Pre-service teachers reported struggling to recognize the relevance of theoretical input when practical application of technology use was lacking (see Johnson et al., 2024). Teacher education should enable participants to learn not only from theory, but also apply knowledge, for example by trying to use ICT (see Hirsch & Rubach, 2024; Fütterer et al., 2025) and learn from the practices of other teachers, including (staged) video vignettes or visiting exemplary schools using ICT and with experienced colleagues (see Aumann et al., 2025; Amdam et al., 2024; Hirsch & Rubach, 2024). Although many studies emphasize the importance of linking theory and practice, they rarely integrate empirical findings in a way that allows participants to engage with research-based evidence. This suggests a missed opportunity to foster evidence-informed professionalism in teacher education—an aspect that should be emphasized more strongly in this context.

Provide Learning from theory, planning and implementation to reflection. What is evident across many of the studies included in this Special Issue is that the learning process follows a

similar structure which closely resembles the learning cycle for teacher education proposed by McDonald et al. (2013). The following phases are proposed by McDonald: introducing and learning about the activity (e.g., through modeling), preparing for and rehearsing the activity (e.g., through collaborative planning), enacting the activity with students (e.g., by co-teaching), analyzing enactment and moving forward (e.g., through video analysis). In the studies included in this Special Issue, participants first receive a theoretical input, which they are then expected to apply independently (see Aumann et al., 2025; Fütterer et al., 2025). In most cases, this is achieved by developing lesson plans that allow for pre-service or in-service teachers to incorporate the newly acquired knowledge into their own teaching practices. These lessons are subsequently implemented in practice and, where possible, reflected upon. In several studies, participants were given the opportunity to practice using technology in their own time, yet this aspect was rarely addressed explicitly or discussed as a deliberate feature of instructional design. The study by Johnson et al. (2024) further supports the importance of planning technology use in lessons and putting this into practice as pre-service teachers criticized the fact that, although theoretical input was provided, opportunities for practical application were missing. This focus directly relates to two further instructional quality dimensions identified in the MAIN-TEACH model, cognitive activation and supporting practice, which emphasize that learning processes are most effective when learners are intellectually challenged and provided with opportunities to apply and consolidate what they have learned. These steps also relate to Tondeurs' idea of instructional design, which states that student teachers need to learn to apply technology in class (Tondeur et al., 2012).

Feedback and Reflection. As described in the MAIN-TEACH model, it is also important to assess learners formatively, i.e., to not only to monitor their learning progress, but also to provide instruction and timely, constructive feedback that supports ongoing development. Studies in this Special Issue indicate that, for learners, receiving feedback on their learning progress, e.g., after engaging in practice, is effective for their competence development (see also Tondeur et al., 2012), but also that they critically reflect on their own teaching experiences. The emphasis on reflection as a key component of the learning process within teacher education and professional development is supported by several studies in this Special Issue (see Aumann et al., 2025; Hirsch & Rubach, 2024; Johnson et al., 2024; Fütterer et al., 2025). Feedback and reflection, as also described by McDonald, either occur at the end of the learning process—after newly acquired content has been applied (see Aumann et al., 2025)—or are implemented formatively throughout the learning process to guide and support ongoing development (Fütterer et al., 2025; Johnson et al., 2024; Hirsch & Rubach, 2024).

Implementation of different stakeholders. Role models emerged across several studies as key elements in fostering digital competence development. As highlighted by Tondeur et al. (2012), the use of role models is one of the central strategies in the SQD model for supporting professional learning. The findings in this Special Issue suggest that role models are most effective when learners are given opportunities to observe digital teaching practices not only through video vignettes, but through structured, authentic learning environments—such as those involving peer observations, mentoring, and in-person modeling within internships (see Aumann et al., 2025; Hirsch & Rubach, 2024). This particularly concerns teachers being not only role models but also peers. Equally important, however, is that both pre-service and in-service teachers are given the opportunity to try implementing their ideas directly with students (see Aumann et al., 2025; Hirsch & Rubach, 2024). While this aspect is less related to the concept of role modeling, it is crucial for ensuring the authenticity of learning environments (see Tondeur et al., 2012), allowing learners to connect theoretical

and empirical input with real-world teaching experiences. Both aspects—learning through role models and engaging in authentic teaching experiences—can be understood as forms of support for active engagement within the MAIN-TEACH framework.

Collaborative learning. Tondeur et al. (2012) emphasize the importance of collaborative learning settings in teacher education as a key strategy for fostering digital competencies. The goal is to enable pre-service teachers to engage in meaningful dialog with peers, discuss and apply newly acquired knowledge, and learn from one another through joint exploration and practice. For in-service teachers, the concept of professional learning communities plays a central role (Amdam et al., 2024; Fütterer et al., 2025). Within these communities, participants collaboratively reflect on the implementation of technology, exchange ideas, and critically discuss the challenges and successes observed in practice. For pre-service teachers, collaborative formats often resemble communities of practice, in which students are exposed to the ideas of their peers, engage in shared discussions, and co-develop solutions (Johnson et al., 2024; Hirsch & Rubach, 2024). Although the dimension of collaboration is not explicitly addressed in the MAIN-TEACH model, the findings of this Special Issue emphasize its empirical relevance as a content-specific teaching strategy, particularly in preparing teachers to use ICT effectively in their professional practice.

6. Future Steps Toward Effective Support in Teacher Digital Professionalism

The contributions in this Special Issue provide empirical evidence that aligns with and expands upon key assumptions of established models such as MAIN-TEACH and SQD. Across the contributions included here, there is consistent evidence that the effectiveness of professional learning environments depends not on individual strategies but rather on their systematic orchestration in a coherent, developmental structure (see Hirsch & Rubach, 2024). These models also offer a valuable orientation for future research, several directions of which are suggested by the authors themselves.

When reflecting upon the contributions to this Special Issue, it is interesting that limited attention has been paid by the researchers included here to the generic-content dimensions of high-quality teaching, i.e., classroom and time management and socio-emotional support. This might have been the case because studies on teaching quality and research on fostering teachers' digital competencies is often not interconnected—neither theoretically nor empirically. This might be because the models of high-quality teaching have been conceptualized to describe the prerequisites of fostering students' rather than teachers' learning outcomes mostly at the K-12 stage (see Praetorius & Gräsel, 2021). Many of the studies in this Special Issue draw on ideas that are closely aligned with established models such as MAIN-TEACH or SQD, even though they do not always explicitly reference these frameworks. From our perspective, making these theoretical foundations more explicit and connecting them through a transdisciplinary lens could be highly beneficial. It would allow for a more integrated understanding of high-quality teaching to be developed, and it would be useful in informing the systematic design of teacher education programs aimed at fostering digital competence. Moreover, although the importance of adaptivity and differentiation is acknowledged in several contributions, these dimensions are often discussed rather than empirically investigated in depth (Annemann et al., 2025; Amdam et al., 2024; Aumann et al., 2025; Hirsch & Rubach, 2024). However, the contributions suggest that heterogeneity in teachers' prior knowledge, interests, and needs must be taken seriously (e.g., Rahden et al., 2025). This suggests that differentiation should go beyond adaptations of materials or structures within a single learning environment and instead involve the design of diverse environments tailored to specific content areas and learning objectives related to digital competence. To obtain knowledge about the diversity of needs,

simulation environments help to identify needs through formative assessments without the risk of real-life consequences (Roeben et al., 2025).

This Special Issue has offered differentiated views on various aspects of professionalization in teacher education and professional development, providing valuable insights into how digital competencies can be supported. While several studies contribute to our understanding of motivational beliefs—such as self-efficacy, perceived usefulness, and intention to use digital tools—there is still limited empirical knowledge on how to effectively foster knowledge and practical skills, particularly among in-service teachers.

In conclusion, the contributions in this Special Issue can be used to inform teacher education and teacher professional development about central preconditions to foster teachers' digital competencies systematically, and they also provide knowledge about effective design-principles as. All scholars provided empirical evidence for the central prerequisites for the high-quality promotion of pre-service and in-service teachers' digital competencies, that is (a) aligning curricula with professional realities, (b) designing authentic learning environments, (c) connecting theory, empirical evidence and practice, (d) providing learning from theory, planning, and implementation to reflection, (e) providing feedback and encouraging reflection, (f) considering different stakeholders, as well as (g) nurturing the conditions for collaborative learning and (h) and the way they are combined and orchestrated to provide high-quality learning opportunities. Thus, we have compiled research on high-quality teaching for the development of teachers' digital competencies. These joint perspectives can be highly fruitful in the endeavor to better understand how the digital competencies of educators can be fostered effectively.

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Article

Acceptance of Pre-Service Teachers Towards Artificial Intelligence (AI): The Role of AI-Related Teacher Training Courses and AI-TPACK Within the Technology Acceptance Model

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Abstract: Based on the technology acceptance model (TAM), pre-service teachers' acceptance of artificial intelligence (AI) is crucial in predicting their intentions to use AI in future teaching, as well as for their actual usage of AI. However, current research offers limited insights into the role of factors regarding usage intentions and behaviors. In particular, AI-related teacher training courses and AI-related technological pedagogical content knowledge (AI-TPACK) might be relevant, but are empirically underinvestigated within the TAM. This study addresses these gaps by investigating the relationships between pre-service teachers' participation in AI-related courses, their self-reported AI-TPACK, their perceptions of AI's usefulness and ease of use, and both their intention and actual usage of AI. Using path models with data from 143 pre-service teachers, the results revealed that participation in AI-related courses related positively to AI-TPACK and perceived AI-related usefulness. Further, AI-TPACK was positively related to perceived AI-related usefulness and ease of use, which in turn positively related to the behavioral intention to use AI in future teaching and the actual usage of AI for profession-related tasks in teacher training. The study results extend the existing research on TAM and highlight the consideration of participation in AI-related courses and AI-TPACK as further factors in understanding pre-service teachers' AI acceptance.

Keywords: artificial intelligence; technology acceptance model; AI-related courses; AI-TPACK; AI acceptance; pre-service teachers

1. Introduction

The rapid implementation of artificial intelligence (AI) into teaching and learning processes contributes to the transformation of educational processes and practices (Adelana et al., 2024; Celik, 2023; Luckin et al., 2022). AI-based tools, such as generative AI (e.g., ChatGPT and DALL-E), adaptive learning platforms, and intelligent tutoring systems, are considered to lead to substantive changes in education that might enhance teaching and learning (Mikeladze et al., 2024; UNESCO, 2024; Zhang et al., 2023). The greatest potential for the use of AI in teaching is seen as improving adaptivity and interactivity by providing learner-centered, personalized teaching strategies (Celik, 2023; Chiu et al., 2024; UNESCO, 2024). However, these benefits can only be fully realized if pre-service teachers are adequately prepared to integrate AI into their future teaching (Ayanwale et al., 2022; Ayanwale et al., 2024; UNESCO, 2024; Yao & Wang, 2024). Several studies

have highlighted that AI acceptance among pre-service teachers is important for their intention to use AI (Islamoglu et al., 2021; Teo et al., 2019; Zhang et al., 2023). To better understand the factors influencing pre-service teachers' AI acceptance, the technology acceptance model (TAM) (Davis, 1989) provides a valuable theoretical framework. The TAM assumes that user acceptance of new technologies is influenced by users' beliefs about technology, i.e., its perceived usefulness and perceived ease of use. These beliefs are critical predictors of users' intention to use a new technology, which in turn is linked to their actual usage behavior (Davis, 1989). However, the application of TAM to the context of AI in teacher education remains limited. Previous studies in the context of AI have highlighted that pre-service teachers' AI acceptance can also be shaped by their participation in AI-related university courses (Park, 2023). University courses and training programs that focus on AI for pre-service teachers have thus gained significant importance for future AI-enhanced teaching (An et al., 2023; Salas-Pilco et al., 2022; Sun et al., 2023; Zhang et al., 2023). These courses aim to equip future teachers with both a foundational understanding of AI technologies and the pedagogical knowledge required to integrate AI meaningfully into their classrooms (Gregorio et al., 2024; UNESCO, 2024). In the context of AI in education, the pedagogical knowledge is described in the model of AI-related technological pedagogical content knowledge (AI-TPACK) (Celik, 2023; Mishra et al., 2023). The AI-TPACK model builds upon the original TPACK model, extending it to include competencies specifically required for navigating the unique affordances of AI technologies compared to those of conventional digital technologies (Chiu et al., 2024; Jang & Lee, 2023; Meß & Guggemos, n.d.; Mikeladze et al., 2024; Ng et al., 2023), such as human-machine dialogues, automatic assessments, and constructive feedback (Mishra et al., 2023). While AI-related courses aim to foster pre-service teachers' AI-TPACK, the combined relationship of these factors with key TAM constructs, such as perceived usefulness and ease of use, has not yet been thoroughly examined. Additionally, studies on AI-related TAM variables for pre-service teachers have predominantly focused on intention, with limited exploration of actual AI usage or AI-TPACK. Existing studies on digital technologies generally suggest a relationship between perceived usefulness and actual technology usage (Scherer et al., 2015), but similar findings are lacking, specifically in the context of AI.

Referring to these gaps, the present study applies the TAM framework to the context of AI and examines the relationships between pre-service teachers' participation in AI-related courses, their self-reported AI-TPACK, perceived AI-related usefulness and ease of use, their intention to use AI in future teaching, and their actual AI usage within teacher training. Understanding how pre-service teachers perceive AI and which factors relate to their intention to and their actual usage of AI is critical for designing teacher training. These insights can support teacher educators, curriculum developers, and policymakers in preparing future teachers for integrating AI meaningfully into classrooms. This is particularly relevant as AI technologies are becoming increasingly prevalent in education (An et al., 2023; UNESCO, 2024; Zhang et al., 2023).

1.1. Artificial Intelligence in the Technology Acceptance Model

The TAM, originally developed by Davis (1989), is a theoretical framework that explains which factors contribute to users' acceptance and adoption of new technologies. The model assumes that users' intention to use new technologies is influenced by their attitudes toward it, which are shaped by specific beliefs about the technologies. At the core of the TAM are two key beliefs that predict technology acceptance: perceived usefulness, which refers to users' beliefs that a digital technology will enhance their performance, and perceived ease of use, which describes how simple and intuitive they find the tool to operate (Davis, 1989). It is assumed that perceived usefulness and perceived ease of use relate to

the intention to use digital technologies as an indicator for the actual use (Davis, 1989). The TAM has been widely applied in educational contexts to investigate how pre-service and in-service teachers accept and adopt digital tools (e.g., Schina et al., 2021; Teo et al., 2019). Some studies have shown that perceived usefulness and perceived ease of use explain pre-service teachers' intention to use different digital technologies (e.g., Joo et al., 2017). This means that if a digital technology—like AI—is perceived by pre-service teachers as highly useful and user-friendly, pre-service teachers are also more likely to accept and intend to teach with that digital technology. Meß and Guggemos (submitted) show in their systematic literature review that the TAM has already been used to explain AI-related acceptance, and that the rare existing empirical evidence confirms that the perceived AI-related usefulness and perceived ease of use are substantially related to pre-service teachers' intention to use AI in their future teaching (Ma & Lei, 2024; Vo & Pancratz, 2023; Zhang et al., 2023). However, there are only a few empirical studies that look at AI acceptance with a focus on pre-service teachers (Zhang et al., 2023). Following the argumentation by Zhang et al. (2023), it is essential to further understand pre-service teachers' AI acceptance due to the increasing importance of AI in teaching and learning processes and its influence on future student learning outcomes. Additionally, previous studies have been primarily limited to behavioral intention to use AI, which is an indicator (Davis, 1989) but not a representation of the actual use of AI. In teacher training, pre-service teachers reported using AI during their studies for academic purposes like writing assistance or time management but also for profession-related tasks like lesson planning for developing and adapting teaching materials or teaching activities (Hsu et al., 2024). There is currently a lack of research examining how TAM constructs—specifically, perceived usefulness and perceived ease of use—relate to this teacher profession-related usage. This is a notable gap, as research on digital technologies in education suggests that, e.g., perceived usefulness, is directly linked to actual use (Scherer et al., 2015). Exploring the relationships between additional TAM constructs and actual AI use among pre-service teachers could offer valuable insights into the factors driving technology adoption in teacher training. The TAM emphasizes the roles of perceived usefulness and ease of use as key predictors of technology acceptance but also points to the influence of further factors on these beliefs (Davis, 1989). In the context of teacher training, factors like pre-service teachers' participation in AI-related courses and AI-related technological knowledge will be discussed in the following sections.

1.1.1. Participation in AI-Related Courses in Teacher Training

Teacher training at university is the first stage of professional development of pre-service teachers and encompasses practices, strategies, and policies that equip teachers with the knowledge, competencies, and ethical guidance needed to teach effectively (Luckin et al., 2022; Salas-Pilco et al., 2022). In the context of digitalization, teacher training is now facing the challenge of adapting to rapidly changing technologies, such as the use of AI in teaching (Ayanwale et al., 2024; Jang & Lee, 2023; Zhang et al., 2023). A lack of professional development opportunities could result in teachers feeling overwhelmed and unprepared when integrating AI into their teaching practice (Kim & Kwon, 2023). In contrast, supporting pre-service teachers in the pedagogical use of AI can help to create a more effective learning atmosphere for students and facilitate the introduction of AI-enhanced teaching in future classrooms (Gregorio et al., 2024). Therefore, global policymakers, such as those participating in the Standing Conference of the Ministers of Education and Cultural Affairs in Germany (2021), where our study was carried out, are encouraging governments to introduce appropriate regulations and training for educators to ensure a human-centered approach to the use of generative AI in education. To achieve these aims, in regards to the AI competency framework for teachers, UNESCO (2024) emphasizes the importance of

preparing teachers to effectively integrate AI tools in education, calling for comprehensive professional development that spans their entire career, from pre-service training to ongoing in-service support. Thus, AI-related courses at university are gaining importance for preparing future teachers to design AI-enhanced teaching (An et al., 2023; Salas-Pilco et al., 2022; Zhang et al., 2023). Current studies are focusing primarily on in-service teachers in teacher education (Zhang et al., 2023), and only a few studies deal with the question of how teacher training can be improved to prepare pre-service teachers for the future teaching implementation of AI (Ayanwale et al., 2022). However, current studies on the evaluation of professional development programs for pre-service teachers focused on designing lessons incorporating ChatGPT have proven to be effective in enhancing pre-service teachers' self-reported AI literacy skills and attitudes (Younis, 2024). Specifically, Younis (2024) found that after participating in such a program, pre-service teachers reported more positive attitudes towards integrating AI tools into their teaching practice and demonstrated improvements in their self-reported AI literacy, particularly in understanding the pedagogical applications of AI. Park (2023) was able to show that after a 15-week extension program that aimed to improve the professionalism of pre-service teachers in AI education, pre-service teachers perceived increased joy in acquiring knowledge about AI tools, increased usefulness of AI in the classroom, and increase AI literacy. Within these AI-related seminars and training programs, the research suggests that pre-service teachers benefit most from practical, experience-based learning environments in the context of AI (Jang & Lee, 2023; Park, 2023; Younis, 2024). However, these implications relate primarily to the promotion of AI-related competencies. No empirical findings exist concerning the relationships between the participation in AI-related courses and pre-service teachers' perceived usefulness and perceived ease of use of AI. Based on the results of studies on digital technologies, it can be shown that the usefulness and ease of use of digital technology could be increased as part of a teacher training course (e.g., Schina et al., 2021).

1.1.2. AI-TPACK

Various studies have considered pre-service and in-service teachers' self-reported technological pedagogical content knowledge (TPACK) (Mishra et al., 2023) as another salient factor in the TAM, which significantly affects teachers' perceptions of usefulness and ease of use (Joo et al., 2017; Teo et al., 2019; Wangdi et al., 2023), their intention to use digital technologies (Max et al., 2023; Sun et al., 2023; Teo et al., 2019), and their actual use (Hsu et al., 2024). Related to AI, most existing studies primarily address teachers' AI literacy, which emphasizes a foundational technological understanding of AI techniques and concepts (Ayanwale et al., 2024) and refers to the skills that allow individuals to critically assess AI technologies, communicate with AI, and utilize it in various contexts (Almatrafi et al., 2024). However, in addition to basic technological knowledge, teachers also need AI-related pedagogical knowledge to critically evaluate and integrate AI into educational settings to foster students' learning (Chiu et al., 2024; Meß & Guggemos, n.d.; Mikeladze et al., 2024; Ng et al., 2023; Ning et al., 2024). As a consequence, the TPACK model has been extended to describe the technological and pedagogical content knowledge required for effectively integrating AI in teaching, resulting in the AI-TPACK model (Celik, 2023; Mishra et al., 2023). The integration of AI within TPACK describes adapting teaching practices to the evolving demands of AI, equipping teachers with the competencies necessary for navigating the unique affordances of AI technologies in teaching (Celik, 2023; Mishra et al., 2023). Just like the original TPACK model, the knowledge dimensions of the extended AI-TPACK model can also be assigned to the digital competence concept as competence-related beliefs (Rubach, 2024; Rubach & Lazarides, 2023). Regarding the TAM, An et al. (2023) showed in their study that in-service teachers' AI-TPACK

predicted the intention to use AI technologies in teaching. However, there are also study from Yao and Wang (2024), who investigated the relationships between pre-service teachers' AI literacy and AI-related intention, revealing no significant results. Current studies only consider AI literacy, perceived usefulness, and ease of use, showing that all three constructs are associated with pre-service teachers' intention to use AI technologies (Ma & Lei, 2024). To date, there have been no studies investigating the relationships between pre-service teachers' AI-TPACK, perceived usefulness, ease of use, behavioral intention, and actual use of AI.

1.2. The Present Study

Several studies grounded in the TAM have explored pre-service teachers' acceptance of various digital technologies (e.g., Islamoglu et al., 2021; Teo et al., 2019). However, only a limited number of studies have extended this model to specifically assess pre-service teachers' acceptance of AI, and even fewer have included factors such as participation in AI-related courses and AI-TPACK. This highlights a significant gap in understanding how these factors jointly contribute to shaping pre-service teachers' acceptance and usage of AI in their future teaching practice. Figure 1 depicts our hypothesized research model, addressing these gaps. Accordingly, this study investigates the following research questions and hypotheses, as outlined in the TAM framework:

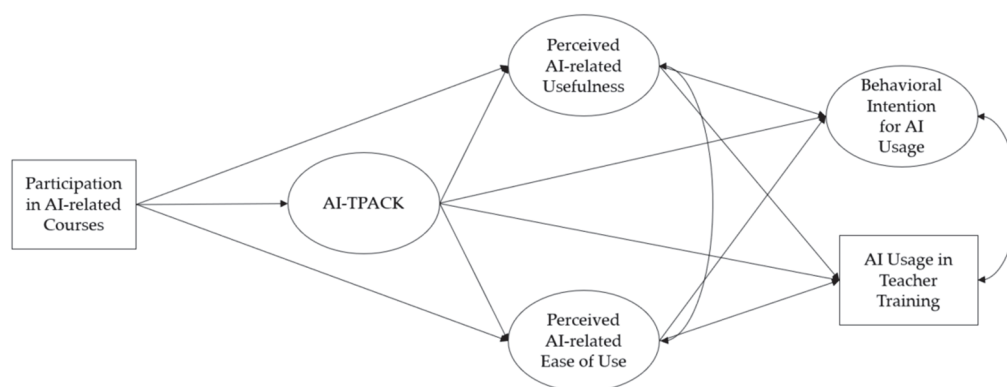


Figure 1. The hypothesized research model.

RQ1: To what extent does pre-service teachers' participation in AI-related courses relate to their self-reported AI-TPACK and their perceptions of AI-related usefulness and ease of use?

H1a. *Pre-service teachers' participation in AI-related courses is positively related with their self-reported AI-TPACK.*

According to study results on the evaluation of AI-related professional development programs for pre-service teachers (Younis, 2024), we also assume that participation in AI-related courses is positively related to competence-related beliefs in terms of self-reported AI-TPACK.

H1b. *Pre-service teachers' participation in AI-related courses is positively related to their perceived AI-related usefulness and ease of use.*

Although there are no results on the direct relationships between AI-related courses and perceived AI-related usefulness and ease of use, studies such as those by Park (2023) and Younis (2024) indicate that pre-service teachers' participation in courses is related to a positive change in attitudes and perceptions of AI. In the context of digital technologies, Schina et al. (2021) were also able to show that the participation in teacher training courses

is related to pre-service-teachers' perception of usefulness and ease of use. Since AI belongs to digital technologies in the broadest sense, it could be assumed that these TAM-related constructs are also related to teacher training courses on AI.

RQ2: To what extent does pre-service teachers' self-reported AI-TPACK relate to their perceptions of AI-related usefulness and ease of use, as well as to their behavioral intention to use AI in future teaching and to their AI usage in teacher training?

H2a. *Pre-service teachers' self-reported AI-TPACK relates positively to their perceived AI-related usefulness and ease of use.*

There is a lack of studies on the relationships between pre-service teachers' AI-TPACK and perceived AI-related usefulness and ease of use; however, there is a large number of results regarding TPACK and perceived usefulness and ease of use illustrating positive correlations (Joo et al., 2017; Teo et al., 2019; Wangdi et al., 2023). Based on these research findings, similar correlations are assumed for the AI context.

H2b. *Pre-service teachers' self-reported AI-TPACK relates positively to their behavioral intention to use AI in future teaching.*

According to the study results of An et al. (2023), in-service teachers' self-reported AI-TPACK was statistically significantly related to their intention to use AI in teaching. It can be assumed that these relationships also exist for pre-service teachers.

H2c. *Pre-service teachers' self-reported AI-TPACK is positively related to their AI usage in teacher training.*

So far, there are no studies investigating the relationships between pre-service teachers' AI-TPACK and their actual use of AI, but study results on TPACK indicate statistically significant positive relationships to the use of digital technologies (Hsu et al., 2024). These results are therefore assumed in context of AI-TPACK.

RQ3: How do pre-service teachers' self-reported AI-TPACK and their perceptions of AI-related usefulness and ease of use relate to their behavioral intention to use AI in future teaching and to their AI usage in teacher training?

H3a. *Perceived AI-related usefulness and ease of use relate positively to behavioral intention to use AI in future teaching.*

Based on existing study results for pre-service teachers (Ma & Lei, 2024; Yao & Wang, 2024; Zhang et al., 2023), positive relationships between perceptions of usefulness and ease of use for AI and intention to use AI in teaching are assumed.

H3b. *Perceived AI-related usefulness and ease of use are positively related to pre-service teachers' AI usage in teacher training.*

In the context of digital technologies, Scherer et al. (2015) demonstrated that perceived usefulness has a positive relationship with the actual use of digital technologies, suggesting that when individuals believe a technology can improve their effectiveness, they are more likely to use it. Although similar studies explicitly examining ease of use in relation to actual usage are scarce, findings of usefulness are also assumed for ease of use in the context of AI.

2. Materials and Methods

2.1. Sample

This study draws on a sample of 143 pre-service teachers enrolled in various German universities, with the majority coming from Brandenburg (42%) and Berlin (13%). Data were collected during the summer semester of 2024, from April to September. The study was approved by the Ethics Committee of the University of Potsdam, Germany. During the acquisition process, the survey link was shared through multiple university newsletters and social media channels focused on teacher training. Outliers were identified by examining the z-scores, with values exceeding ± 3 considered as outliers. Consequently, 41 cases with z-scores above ± 3.00 were excluded from further analysis. The remaining 143 pre-service teachers included in our sample were enrolled in either a bachelor's (56%) or master's (42%) program in teacher training. Pre-service teachers predominantly identified as women (60%), and most (43%) were between 21 and 24 years old. The majority of the pre-service teachers had not yet participated in AI-related courses at the university (56%), with only 33% having had such experience. The sample was almost evenly divided between first-generation academic students (43%) and those from academic households (47%).

2.2. Measures

The online questionnaire consisted of two parts: the first part collected socio-demographic information, and the second part measured pre-service teachers' participation in AI-related courses, their perceived AI-related usefulness and ease of use, their self-reported AI-TPACK, their behavioral intention for AI usage in future teaching, and their AI usage in teacher training. The items were originally presented in German and are translated into English in this paper. The wording of all items is provided in Table A2 in Appendix A.

Socio-Demographics. The pre-service teachers' gender was assessed using categorical coding (1 = female; 2 = male; 3 = diverse). As there were no responses regarding "diverse", we recoded the item as binary (1 = female; 2 = male). Age was assessed with a categorical scale (1 = below age 20, 2 = 21 to 24 years, 3 = 25 to 30 years, 4 = 31 to 34 years, and 5 = 35 years or more). The pre-service teachers were also asked whether they were aiming for a bachelor's or master's degree at the time of the survey and which academic semester they were currently attending. With regards to educational background, the pre-service teachers were asked if members of their close family obtained an academic professional qualification (university of applied sciences; college; university).

Participation in AI-related Courses. The pre-service teachers were asked how many courses they had attended during their teacher training that dealt with AI in teaching. The response options were categorized as 1 = none, 2 = 1–2 courses, 3 = 3–4 courses, and 4 = more than 5 courses. The answers were recoded into a binary format for the analyses (1 = none, 2 = at least one AI-related course).

Perceived AI-related Usefulness. To assess pre-service teachers' perceived usefulness of using AI in teaching, they were asked to rate four items from Choi et al. (2023). The items were reformulated for teachers, so that an example item states: "Using AI in the teaching profession would improve my performance." Each item was rated on a five-point Likert scale ranging from 1 (do not agree at all) to 5 (fully agree). One item was excluded from the analysis due to its insufficient contribution to the internal consistency of the scale. After exclusion, the internal consistency of the scale used in the present study was $\omega = 0.88$.

Perceived AI-related Ease of Use. A scale from An et al. (2023) was used to assess pre-service teachers' perceived ease of use of AI in teaching. Four items were rated on a five-point Likert scale ranging from 1 (do not agree at all) to 5 (fully agree). An example

item is “AI teaching systems are easy to operate for me.” The internal consistency of the scale in the present study was $\omega = 0.93$.

AI-TPACK. Pre-service teachers’ AI-related technological pedagogical content knowledge was assessed through a scale created by An et al. (2023). The items were reformulated for the general use of AI in teaching, so that one example reads: “I know how to use appropriate strategies with AI to help students learn better.” From the original scale with nine items, four items were excluded due to low reliability, to ensure overall consistency. The shortened scale, as applied in the present study, has an internal consistency of $\omega = 0.94$.

Behavioral Intention for AI Usage. To assess pre-service teachers’ behavioral intention to use AI technologies in future teaching, they were asked to rate three items from Galindo-Domínguez et al. (2023) on a five-point Likert scale ranging from 1 (do not agree at all) to 5 (fully agree). An example item is “I would love to be able to use artificial intelligence in my work as a teacher”. The internal consistency of the scale used in the present study was excellent, with $\omega = 0.88$.

AI Usage in Teacher Training. On a scale based on the work of Garrel et al. (2023), pre-service teachers reported how often they use AI in teacher training for (a) the preparation of teaching materials, (b) recommendations for relevant teaching materials, (c) planning teaching units, and (d) the generation of test questions. The items were answered on a six-point Likert scale ranging from 1 (never) to 6 (very often). The internal consistency, calculated for the scale used in the present study, was $\omega = 0.87$.

2.3. Statistics

To test our hypotheses, we conducted a path model using Mplus 8.10. For the path model structure, we followed the relationship assumptions of the underlying TAM, modified by adding additional factors. Specifically, pre-service teachers’ participation in AI-related courses is modeled as a factor related to AI-TPACK, perceived AI-related usefulness, and perceived ease of use. AI-TPACK, in turn, is also modeled as a factor for perceived usefulness, perceived ease of use, behavioral intention to use AI, and actual use of AI in teacher training. Following TAM, usefulness and ease of use are analyzed in relation to both behavioral intention for AI usage in future teaching and AI usage in teacher training. In contrast to the TAM assumptions, AI usage in teacher training is not modeled in relation to behavioral intention, given the context of pre-service teachers. Most pre-service teachers are not yet actively teaching during their studies. Thus, their actual AI usage reflects professional-related tasks within their teacher training, rather than teaching applications. As a result, we did not assume direct relationships between the behavioral intention for AI usage and AI usage in teacher training. Within the path model, the constructs of AI-TPACK, perceived usefulness, perceived ease of use, behavioral intention to use AI, and actual use of AI in teacher training are modeled as latent, whereas only participation in AI-related course is modeled as a manifest binary variable.

The evaluation of model fit was carried out using several key indicators, as recommended by Kline (2023), including χ^2 , CFI (comparative fit index), TLI (Tucker–Lewis Index), RMSEA (root mean square error of approximation), and SRMR (standardized root mean residual). Following established guidelines, values above 0.90 for CFI and TLI, and below 0.08 for both RMSEA and SRMR, were considered indicative of an acceptable fit (Hu & Bentler, 1999). All path analyses utilized the maximum likelihood estimation with robust standard errors (MLR). The variance explained for the dependent variables within the path models was estimated using the R^2 measure.

In the initial path model analyses, we included covariates shown to be statistically significant in previous AI-related studies, specifically pre-service teachers’ gender (Zhang et al., 2023) and academic semester (Zinn et al., 2022). However, these covariates did not

show statistically significant relationships in our path models and negatively impacted the overall model fit. Consequently, the final analyses presented in the results section were conducted without these covariates. For comprehensive documentation, we have included the path model with covariates in the Appendix A (see Table A1).

3. Results

3.1. Descriptive Statistics

Table 1 demonstrates the means, standard deviations, and bivariate Pearson's correlations of the key constructs. The correlation analyses show that pre-service teacher participation in AI-related courses was positively associated with all constructs that were included in the analyses, with AI-TPACK showing the highest correlation coefficient. Among the AI acceptance constructs, perceived AI-related usefulness and ease of use had statistically significant positive correlations with AI-TPACK, AI usage in teacher training, and with each other. However, only perceived usefulness correlated positively with behavioral intention for AI usage. Furthermore, the results indicate that AI-TPACK and behavioral intention for AI usage were both statistically significantly positively correlated with AI usage in teacher training.

Table 1. Bivariate Pearson's correlations among analyzed constructs ($N = 143$).

	<i>M</i>	<i>SD</i>	Perceived AI-Related Usefulness	Perceived AI-Related Ease of Use	AI-TPACK	Behavioral Intention for AI Usage	AI Usage in Teacher Training
Participation in AI-related courses	1.38	0.49	0.34 ***	0.21 *	0.45 ***	0.26 *	0.27 **
Perceived AI-related usefulness	3.76	0.90	-	0.32 **	0.36 ***	0.68 ***	0.44 **
Perceived AI-related ease of use	2.96	1.04		-	0.43 ***	0.15	0.52 ***
AI-TPACK	2.36	0.90			-	0.19	0.41 ***
Behavioral intention for AI usage	4.08	0.73				-	0.34 ***
AI usage in teacher training	2.36	1.24					-

Notes: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

3.2. Path Model Analyses

The path model is depicted in Figure 2, and the standardized coefficients are reported in Table 2. The results of the path model indicate that participation in AI-related courses was positively related to AI-TPACK and perceived AI-related usefulness. No statistically significant relationships occurred between participation in AI-related courses and pre-service teachers' perceived ease of use. AI-TPACK was positively linked to both the perceived AI-related usefulness and ease of use. However, there were no statistically significant relationships between AI-TPACK and pre-service teachers' behavioral intention to use AI in future teaching or their actual use of AI in teacher training. Perceived usefulness is statistically significantly related to both behavioral intention for AI usage and actual AI usage in teacher training. Pre-service teachers' perceived AI-related ease of use, by contrast, only showed positive relationships with the AI usage in teacher training. The path model achieved an acceptable fit to the data, as follows: $\chi^2 = 227.22$, $df = 150$, CFI = 0.95, TLI = 0.93, RMSEA = 0.06, and SRMR = 0.05.

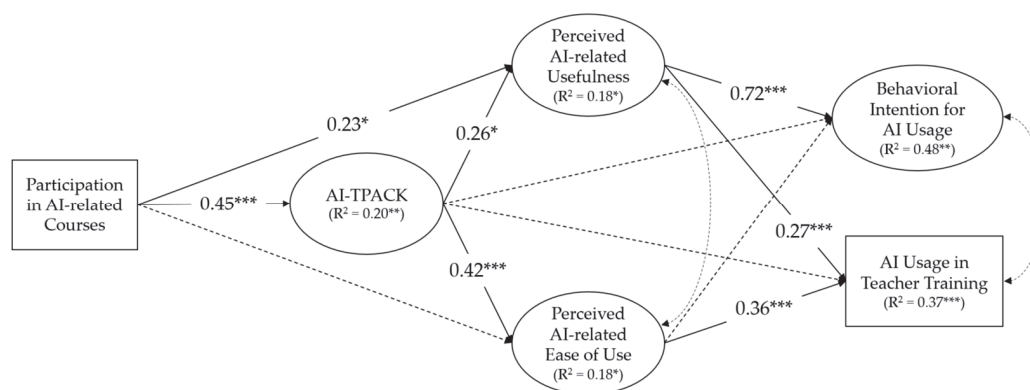


Figure 2. Path model analyses comparing pre-service teachers' participation in AI-related courses, self-reported AI-TPACK, perceived AI-related usefulness and ease of use, behavioral intention to use AI in future teaching, and AI usage in teacher training. *Notes:* standardized effects are reported. Straight lines display statistically significant paths. Dashed straight lines display tested but statistically non-significant paths. Dashed curved lines show statistically non-significant correlations. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Table 2. Standardized coefficients of the path model ($N = 143$).

	AI-TPACK			Perceived AI-Related Usefulness			Perceived AI-Related Ease of Use			Behavioral Intention for AI Usage			AI Usage in Teacher Training		
	β	SE	p	β	SE	p	β	SE	p	β	SE	p	β	SE	p
Participation in AI-related courses	0.449	0.078	0.000	0.235	0.112	0.000	0.025	0.102	0.808	-	-	-	-	-	-
AI-TPACK	-	-	-	0.260	0.121	0.032	0.417	0.102	0.000	-0.045	0.114	0.690	0.165	0.120	0.169
Perceived AI-related usefulness	-	-	-	-	-	-	-	-	-	0.722	0.136	0.000	0.266	0.092	0.004
Perceived AI-related ease of use	-	-	-	-	-	-	-	-	-	-0.061	0.094	0.518	0.362	0.093	0.000

4. Discussion

The acceptance of digital technologies by pre-service teachers has already been shown to be important for their behavioral intention to use these technologies in future teaching and their actual use of technologies (e.g., Islamoglu et al., 2021; Teo et al., 2019). However, the application of the TAM in the context of AI, as well as an examination of factors related to pre-service teachers' AI acceptance, has so far been limited. Addressing this research gap, the present study investigated the roles of AI-related courses and AI-TPACK as they relate to the TAM constructs—perceived usefulness; perceived ease of use—and to both the behavioral intention and actual usage of AI in teacher training. In the following section, we discuss our study findings in detail, along with their theoretical and practical implications.

4.1. Participation in AI-Related Courses, AI-TPACK, and Perceptions of AI-Related Usefulness and Ease of Use

Regarding the first research question (RQ1), the results indicate that pre-service teachers who participated in AI-related courses in teacher training reported high AI-TPACK (H1a) and a high perception of usefulness of AI in teaching (H1b). As expected (H1a), the positive relationships with AI-TPACK aligned with existing study results showing that AI-related professional development programs for pre-service teachers were positively related to self-reported competence beliefs in terms of AI-TPACK (Younis, 2024). These results may indicate that the participation in AI-related courses is relevant to how pre-service teachers perceive their own AI-TPACK. According to our assumption (H1b), the participation in

AI-related courses was positively related to pre-service teachers' perception of usefulness of AI. Contrary to our assumption (H1b), pre-service teachers who participated in AI-related courses did not report statistically significantly high levels of perceived AI-related ease of use. Previous findings regarding digital technologies showed that participating in digital-related teacher training courses related positively to pre-service teachers' perceived usefulness and ease of use (Schina et al., 2021). Our results support these relationships for usefulness in the context of AI, but not for ease of use. Thus, Hypothesis 1b can thus only be partially confirmed. The absence of relationships between course participation and perceived ease of use in our results could possibly be linked to the content of the AI-related courses. It is possible that the AI-related courses prioritized pedagogical applications of AI over technical understanding, consistent with teacher training programs focused on instructional use. In the studies of Park (2023) and Younis (2024) on AI-focused courses, while an understanding of AI was addressed, the main emphasis was on subject-specific instruction regarding designing with AI and promoting student engagement by using AI. This could explain why pre-service teachers who have participated in AI-related courses report perceiving AI as useful because the courses are more likely to teach how AI can be used for teaching to increase productivity and effectiveness. These assumptions should be tested in future studies, taking into account course content.

4.2. AI-TPACK and Perceived AI-Related Usefulness, Ease of Use, Behavioral Intention to Use AI, and Actual Usage of AI in Teacher Training

Based on the TAM, the second research question (RQ2) examined the extent to which pre-service teachers' AI-TPACK is related to the constructs of their acceptance—perceived usefulness and ease of use (H2a)—as well as their AI-related behavioral intention (H2b) and actual use in teacher training (H2c). Previous studies on digital technologies have demonstrated positive relationships between TPACK and both perceived usefulness and ease of use for pre-service teachers (Joo et al., 2017). Our study provides the first results on these relationships in the AI context, since the results indicate that pre-service teachers' self-reported AI-TPACK was positively related to their perceived AI-related usefulness and ease of use. The results suggest that pre-service teachers with a high AI-TPACK are more likely to perceive AI as both useful and easy to use. Hypothesis 2a can thus be confirmed. In contrast, Hypotheses 2b and 2c, which posited that AI-TPACK would be related to behavioral intention to use AI and actual AI usage, were not supported. This diverges from findings for in-service teachers showing positive relationships between AI-TPACK and intention to use AI (An et al., 2023). A possible explanation for these differences could be that our study focused on pre-service teachers, whereas An et al. (2023) examined in-service teachers. Supporting our findings, Yao and Wang (2024), who also studied pre-service teachers, found no statistically significant relationships between self-reported AI literacy and the behavioral intention to use AI. With regard to actual AI usage, studies specifically focusing on pre-service teachers and AI are lacking. However, previous research on digital TPACK found positive relationships between TPACK and in-service teachers' use of digital technologies (Hsu et al., 2024). These discrepancies may reflect the difference in teaching experience between pre- and in-service teachers. In-service teachers' practical experience may enhance the application of AI-TPACK, strengthening the intention and actual use of AI. These findings underscore the need for further research that distinguishes between pre- and in-service teachers, focusing on how the context of professional experience may affect the relationships between AI-TPACK on AI-related behaviors in terms of behavioral intention and actual usage. Furthermore, based on the TAM, it could be argued that AI-TPACK may not have a direct relationship with behavioral intention or actual use of AI. Mediation analyses were not conducted in the present study, which is why this assumption cannot be made on the basis of the results. But Yao and Wang (2024) found

an indirect relationship between pre-service teachers' AI literacy and their intention to use AI, mediated by perceived usefulness and ease of use. Consequently, future research should consider examining AI-TPACK's potential indirect relationship within TAM to fully capture its role in shaping behavioral intention to use AI and the actual usage of AI among pre-service teachers.

4.3. Perceived AI-Related Usefulness, Ease of Use, Behavioral Intention to Use AI, and Actual Usage of AI in Teacher Training

The third research question (RQ3) addressed the relationships between pre-service teachers' acceptance of AI in teaching, their behavioral intention to use AI in future teaching, and their actual use of AI in teacher training for profession-related tasks. In alignment with the TAM, our findings demonstrated that perceived AI-related usefulness positively related to the behavioral intention to use AI in teaching (H3a). Specifically, if pre-service teachers perceive AI as useful, they are more likely to intend to use it in their future teaching practice. Similar results were shown in previous studies (Ma & Lei, 2024; Yao & Wang, 2024; Zhang et al., 2023). However, contrary to the assumptions in the TAM and previous study results, no statistically significant relationships were found between pre-service teachers' perceived ease of use and intention to use AI. Hypothesis 3a is thus partially confirmed for AI-related usefulness. Previous studies (Yao & Wang, 2024; Zhang et al., 2023) have already observed that perceived AI-related usefulness is often a stronger predictor than ease of use for behavioral intention, with higher correlation coefficients typically observed for usefulness. Our results are consistent with these findings, as only perceived AI-related usefulness was statistically significantly positively related to pre-service teachers' intention to use AI. Zhang et al. (2023) explain that pre-service teachers are primarily interested in using AI for enhancing instructional effectiveness and for fostering learning outcomes; therefore, they perceive a high intention to use AI if they also rate the usefulness as high. This focus on productivity and impact may lead them to perceive high usefulness, which in turn strengthens their intention to use AI, while ease of use may be less critical in this context. Additionally, this could indicate that pre-service teachers may place greater importance on the pedagogical benefits of AI tools rather than on their technical usability. This focus aligns with the objectives of teacher training programs, which emphasize the development of didactic and pedagogical strategies. As a result, pre-service teachers may prioritize how AI can be used to improve teaching and learning processes over how easy it is to operate these tools. Since teacher education aims to equip future teachers with the skills to integrate technologies meaningfully into their classrooms, the perceived usefulness of AI becomes a more decisive factor in shaping their intention to use AI (An et al., 2023; Ma & Lei, 2024; Scherer et al., 2015; Yao & Wang, 2024; Zhang et al., 2023).

Moreover, we examined the relationships between perceived AI-related usefulness, ease of use, and the actual usage of AI for profession-related tasks (H3b). Our results showed that both the perceived usefulness and the perceived ease of use positively related to pre-service teachers' use of AI in teacher training. Specifically, pre-service teachers who reported that they perceived AI for teaching as useful and easy to use also reported that they use AI in their teacher training to plan lessons, design teaching materials, and develop test questions. This finding is consistent with the work of Scherer et al. (2015), which showed that in-service teachers' perceived usefulness of digital technologies was linked to its use in teaching. Our study extends this research to pre-service teachers, highlighting that for AI, both perceived usefulness and ease of use are positively related to its actual usage during teacher training.

4.4. Limitations and Future Steps

The following limitations should be considered when interpreting the findings of the present study. First, the sample is limited to student teachers from Germany, more than half of whom came from two out of sixteen federal states. Moreover, the sample size is 143 pre-service teachers and is therefore quite small. These aspects limit the generalizability of the findings. Future studies should include a larger and more heterogeneous group of pre-service teachers.

Second, given that this study utilizes cross-sectional data, our model examines relationships rather than predictive or causal effects. This design does not allow for tracking whether, e.g., pre-service teachers' self-reported AI-TPACK and perceived usefulness or ease of use develops as they progress through their training or specifically after their participation in an AI-related course. With regard to our results, it could also be possible that pre-service teachers are more likely to attend AI-related courses because they already consider AI to be useful in teaching or because they already rate their AI-TPACK as high. Therefore, these relationships should be examined longitudinally. In this context, longitudinal data could also be used to identify possible mediation effects of perceived AI-related usefulness and ease of use for the relationships between AI-TPACK, behavioral intention to use AI, and actual usage of AI.

Lastly, we do not have any information on the AI courses attended, so we cannot consider, e.g., the courses' duration, quality, or content. Taking these aspects into account would support the interpretation of statistically identified relationships. In the context of AI-related courses, it is already known that, if they have practical components, these are particularly related to pre-service teachers' AI competencies (Jang & Lee, 2023; Park, 2023; Younis, 2024). Additional information on the courses should thus be assessed in future studies. Additionally, the study did not consider information on the specific AI tools used by pre-service teachers during their teacher training. Different AI tools may have varying impacts on pre-service teachers' acceptance toward AI integration. Future research should explore how specific AI tools relate to these factors to better inform the design of effective teacher training programs.

4.5. Theoretical and Practical Implications

The theoretical implications lie in the extension of the TAM to include AI-related courses, as well as AI-TPACK, as additional factors that are important for pre-service teachers' perceived AI-related usefulness, ease of use, behavioral intention to use AI in future teaching, and the actual usage of AI in teacher training. Furthermore, measuring pre-service teachers' actual AI use in profession-related tasks, rather than focusing solely on their behavioral intention, provides a concrete perspective on AI acceptance in teacher training. This expands the TAM by illustrating how pre-service teachers apply AI to teaching-relevant activities, despite limited teaching experience. Capturing this usage could offer a preliminary indication of pre-service teachers' AI integration into teaching practices. The expansion of the TAM contributes to a more comprehensive understanding of the relationships that could be relevant for pre-service teachers' AI acceptance.

Given the growing adoption of AI in teaching and learning processes (Luckin et al., 2022), the participation in AI-related courses may be relevant for pre-service teachers' AI-TPACK and their perceived AI-related usefulness, which in turn are related to the intention and actual usage of AI. Practical implications for teacher educators suggest that AI-related courses in teacher training should emphasize how AI can be integrated into teaching to enhance instructional processes and improve learning outcomes. Policymakers and curriculum developers may also benefit from these findings by integrating AI-related course content aimed at supporting pre-service teachers' AI-TPACK into standardized

teacher training guidelines, ensuring that future educators are adequately prepared for AI-enhanced teaching. Through these efforts, pre-service teachers may be more likely to perceive AI as useful, which could positively relate to their intention to use AI in teaching and increase their usage of AI for profession-related tasks during their teacher training.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the Ethics Committee of University of Potsdam, Germany (13/2024).

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

Data Availability Statement: Data are contained within the article.

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

Appendix A

Table A1. Standardized coefficients of the path model with covariates of pre-service teachers' gender and academic semester ($N = 143$).

	AI-TPACK			Perceived AI-Related Usefulness			Perceived AI-Related Ease of Use			Behavioral Intention for AI Usage			AI Usage in Teacher Training		
	β	SE	p	β	SE	p	β	SE	p	β	SE	p	β	SE	p
Participation in AI-related courses	0.445	0.081	0.000	0.283	0.612	0.643	−0.015	0.104	0.884	-	-	-	-	-	-
AI-TPACK	-	-	-	0.272	0.117	0.020	0.437	0.097	0.000	−0.039	0.120	0.746	0.097	0.171	0.572
Perceived AI-related usefulness	-	-	-	-	-	-	-	-	-	0.659	0.144	0.000	0.563	0.412	0.172
Perceived AI-related ease of use	-	-	-	-	-	-	-	-	-	0.014	0.090	0.873	0.348	0.118	0.003
Gender	−0.018	0.091	0.841	−0.588	1.260	0.641	0.136	0.085	0.111	−0.119	0.083	0.153	−0.481	10.112	0.665
Academic semester	0.040	0.085	0.637	0.433	3.537	0.903	−0.170	0.104	0.103	0.078	0.083	0.153	0.107	0.081	0.189

Notes: Model fit: $\chi^2 = 281.32$, $df = 183$, CFI = 0.93, TLI = 0.92, RMSEA = 0.06, and SRMR = 0.05.

Table A2. Item wording.

Participation in AI-related Courses	
<i>How many courses did you attend during your teacher training program that dealt with AI in teaching?</i>	
Perceived AI-related Usefulness	
-	Using AI in the teaching profession would improve my performance.
-	Using AI in the teaching profession would enhance my effectiveness.
-	I find AI to be useful in teaching profession.
Perceived AI-related Ease of Use	
-	AI teaching systems are easy to operate for me.
-	I think AI teaching systems are very simple.

Table A2. Cont.

-	I can easily master the skills of using AI teaching systems.
-	The operation of AI teaching systems is clear.
AI-TPACK	
-	I know how to use appropriate strategies with AI to help students learn.
-	I know how to use appropriate strategies with AI to help students better practice their skills.
-	I know how to use appropriate strategies with AI to help students learn better.
-	I know how to use the strategy of personalized guidance to improve students' skills with the help of AI.
-	I know how to use appropriate strategies to provide students with opportunities to use their skills with the help of AI.
Behavioral Intention for AI Usage	
-	I am willing to use AI in my teaching practice.
-	I am willing to explore new opportunities for integrating AI into teaching and learning processes.
-	I would love to be able to use AI in my work as a teacher.
AI Usage in Teacher Training	
<i>As part of my teacher training program, I use AI . . .</i>	
-	for the provision of teaching materials.
-	for recommendations for relevant teaching materials.
-	for planning teaching units.
-	for the creation of exam questions.

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Article

Simulations in Teacher Education: Learning to Diagnose Cognitive Engagement

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Abstract: Technology has shown to be beneficial for initiating cognitive engagement. In the present study, cognitive engagement was conceptualized by the ICAP framework, proposing four levels of cognitive engagement (interactive, constructive, active, passive), which can be determined from observable student activities. To initiate cognitive engagement, teachers require diagnostic skills. With this study, we aimed to foster those skills. We designed and validated a simulation with $N = 213$ pre-service teachers to investigate the validity of the simulation. Moreover, we evaluated the difficulty of diagnosing the levels of cognitive engagement within planning and implementing lessons. We used linear regressions for the validation and confusion matrices for insights into the diagnostic process. The study results show a varying difficulty of diagnosing levels of cognitive engagement due to (a) challenges in inferring the involved cognitive processes and (b) different phases of teaching. Levels of cognitive engagement that require inferential processes to identify them are more difficult to diagnose. This highlights the importance of adding scaffolds to our simulation to help pre-service teachers understand the processes of generating knowledge and co-generating knowledge. More importantly, the study reveals shortcomings of the ICAP framework and presents first suggestions for its further development.

Keywords: cognitive engagement; simulation; technology-related diagnostic skills; difficulty of diagnosing levels of cognitive engagement

1. Introduction

It has become increasingly common to use technology in lessons to support learning at school. However, the use of technology only improves the quality of a lesson if it is implemented in an effective way (Quast et al., 2021; Wekerle et al., 2022). One way to achieve such an improved lesson quality is by planning and implementing technology in a cognitively engaging way (Sailer et al., 2024; Stegmann, 2020; Wekerle et al., 2024). For this, teachers require skills to combine pedagogical knowledge (PK) with technological knowledge (TK; Koehler et al., 2013; Willermark, 2018). If teachers integrate knowledge about cognitive engagement (PK) and knowledge about the appropriate tools for their pedagogical goals (TK), they develop technological pedagogical knowledge (TPK).

Teachers use their TPK in different phases of teaching, e.g., when planning and when implementing a lesson (DCB, 2017; Ertmer & Ottenbreit-Leftwich, 2010). Ideally, when planning a lesson, teachers diagnose the levels of cognitive engagement within their lesson

plans and check the alignment of the task and learning goal. When implementing a lesson, teachers diagnose their students' current cognitive engagement. Novices may struggle with planning and implementing cognitively engaging technology-supported lessons. To scaffold the acquisition of the respective skills, novices could start with identifying the cognitive engagement in existing lesson plans (Belland et al., 2017; Quintana et al., 2004). This approach may support novices in learning how to plan cognitively engaging technology-supported lessons. To train the implementation of such lessons, instead of diagnosing actual students' cognitive engagement, novices can train on representations of students' learning activities (e.g., generated students' screen-videos or products).

In the present study, the skills to diagnose cognitive engagement in technology-supported lesson plans (i.e., a lesson plan that includes digital tools or media) and in students' technology-related activities are conceptualized as *technology-related diagnostic skills*. Even though diagnostic skills are an important part of teachers' professional knowledge, they are underrepresented in pre-service teacher training (Kramer et al., 2021). As a result, in-service teachers are often not well prepared for making these diagnostic decisions in the actual professional setting (Heitzmann et al., 2019; Oser, 2001). Therefore, it may be helpful to start acquiring technology-related diagnostic skills as soon as in the first phase of teacher training (Kramer et al., 2021). Here, simulations may be a useful tool (Chernikova et al., 2020). Simulations approximate practice (Grossman et al., 2009) while, at the same time, reducing the complexity of real professional settings (Heitzmann et al., 2019). In our study, we therefore aimed at fostering technology-related diagnostic skills in a simulation-based environment. While there is evidence that simulations support the acquisition of complex skills (Chernikova et al., 2020) and that cognitive engagement enhances technology-related learning (Sailer et al., 2024), there is a research gap regarding which types of diagnostic decisions are particularly difficult to make. With this study, we want to examine the difficulty of diagnostic decisions in detail in order to find out how to efficiently and effectively design a simulation that aims at enhancing technology-related diagnostic skills regarding cognitive engagement.

1.1. Technology-Related Diagnostic Skills as Part of Technology-Related Teaching Skills

When teachers make diagnostic decisions, they usually base them on what they observe in and outside of their classroom (Schrader, 2013). A diagnosis involves classifying the forms and causes of phenomena such as cognitive engagement. These forms and causes are often latent or hidden rather than directly observable, requiring identification through visible cues (e.g., a student creating a complex mind map) and inferences based on professional knowledge. A diagnosis typically acts as a decision point that guides actions and interventions that are aimed at addressing and improving the identified problem (Heitzmann et al., 2019). Thus, diagnosing is based on inferring and categorizing observed phenomena, such as cognitive engagement. To facilitate access to information about such hidden phenomena, teachers can harness technology in various ways. In this case, technology supports teachers in terms of generating knowledge about their students. Technology can also support students. If implemented in an effective and efficient way, technology has the potential to foster students' learning processes, especially when cognitively engaging them (Sailer et al., 2024). To guarantee such a beneficial and efficient technology use, it is vital for teachers to be able to diagnose aspects like students' current levels of cognitive engagement and, if necessary, to readjust the task so that students are engaged at the desired level (DCB, 2017). The necessary diagnostic skills for this process require teachers to combine their pedagogical knowledge (PK, i.e., knowing how to cognitively engage students) and technological knowledge (TK; Koehler et al., 2013). Within the present study, we call these diagnostic activities technology-related diagnostic skills. With this term, we

refer to the activity of diagnosing the cognitive engagement of learning goals, tasks, and student activities—all within a simulation. The term *technology-related* refers to a certain use of technology in terms of a digital tool or digital medium within the planning and implementing process of a lesson. However, the technology use itself is not diagnosed or analyzed. We define diagnostic skills as the ability to apply knowledge within a professional context. Thus, diagnostic skills require *conceptual* knowledge (i.e., theoretical knowledge like frameworks), as well as *action-oriented* knowledge (i.e., teachers putting theoretical knowledge into practice; Kopp et al., 2008). When planning and implementing cognitively engaging technology-supported lessons, teachers apply their action-oriented knowledge.

Planning and implementing lessons represent the first two phases of the teaching process, which are followed by the phases of evaluating and sharing lessons (DCB, 2017; Ertmer & Ottenbreit-Leftwich, 2010). We assume that each phase requires specific diagnostic skills. The first phase of teaching—planning a lesson—includes defining learning goals and tasks. Ideally, when designing cognitively engaging lesson plans, teachers reflect on the potential cognitive engagement that is required to reach a specific learning goal. Based on this learning goal, teachers create tasks that have the potential to initiate the level of cognitive engagement that is aimed at by the learning goal. Thus, putting thought into the level of cognitive engagement that matches the learning goal allows teachers to select an appropriate level of cognitive engagement for the respective tasks (Chi & Boucher, 2023). When planning lessons, teachers may also consider implementing technology (Jiménez Sierra et al., 2023). Used in a cognitively engaging way, technology is beneficial for the learning process (Sailer et al., 2024). This requires teachers to design technology-supported lessons that align with students' needs, thereby enhancing effective learning processes (Steffens, 2006; Wekerle et al., 2022). For learning goals and tasks, it is only possible to predict the cognitive engagement that may be achieved in the classroom later on. Therefore, for learning goals and tasks, only the *potential* cognitive engagement can be diagnosed. In contrast, in the implementation phase, the *actual* cognitive engagement can be diagnosed through observing students and analyzing their products. The implementation phase focuses on assessing students' activities and diagnosing whether the activities are carried out at the desired level of cognitive engagement. In this phase, the teachers monitor their students to assess different aspects of their students' behavior, skills, and cognitive processes (DCB, 2017).

We argue that the diagnostic skills that are needed for the planning and the implementation phase differ from each other. For the planning phase, teachers' diagnostic skills focus on estimating which level of cognitive engagement can be achieved by a certain learning goal and on matching it to a task. For the implementation phase, diagnostic skills in terms of observing students' activities and determining their current level of cognitive engagement are required. In the following, we will elaborate on how we conceptualize (levels of) cognitive engagement.

1.2. Cognitive Engagement

Several studies show that cognitive engagement is an important aspect of effective and efficient teaching and learning (Kunter & Voss, 2011; Sailer et al., 2024; Stegmann, 2020). More broadly, cognitive engagement describes the use of cognitive strategies (Chi et al., 2018). In this paper, we conceptualize it using the ICAP framework, which works with the acronym for four levels of cognitive engagement: interactive, constructive, active, and passive (Chi & Wylie, 2014). We decided to use the ICAP framework, as it is evidence-based (Chi et al., 2018) and offers teachers a heuristic to differentiate the complex concept of

cognitive engagement. Moreover, studies found that the student activities that are proposed by the framework are beneficial for the learning process (Sailer et al., 2024; Stegmann, 2020).

According to this framework, students' learning activities can be categorized into four levels. Each level entails different cognitive processes regarding knowledge change (Wekerle et al., 2024). When carrying out a learning activity, students can be cognitively engaged on one of those four levels of engagement (i.e., passive, active, constructive, interactive). In the following, we will describe the knowledge change process and give examples of students' activities for each level of cognitive engagement.

The knowledge change process for the *passive* level is storing information. According to Chi and Wylie (2014), this information can later be recalled in a similar context. The passive level of cognitive engagement entails student activities in which students merely attend to the instructional material and absorb the information from that material. Students are, however, not overtly active, e.g., they do not take notes while listening, reading, or watching the instructional material. Typical student activities for the passive level are watching an explainer video, listening to a podcast or a lecture, and reading a text.

The *active* level of cognitive engagement, additionally to storing information, entails integrating information. Chi et al. (2018) describe that the student activities include a certain motoric action. However, not every motoric action can be determined as active engagement but only those in which students pay attention to the activity, e.g., by manipulating the instructional material. Typical active student activities are taking notes while listening to a lecture, manipulating a text by highlighting words or paragraphs, or pausing/rewinding a video.

Constructive student activities imply that the students generate knowledge that goes beyond the instructional material that is presented by the teacher (Chi & Wylie, 2014). Thus, constructive cognitive engagement goes beyond merely manipulating the instructional material; instead, students infer new output or create new products. Typical constructive activities are reflecting, creating concept maps, (self-)explaining, and taking notes or creating summaries that include their own thoughts (i.e., not just copying the text but using their own words).

Chi et al. (2018) explain that the *interactive* level of cognitive engagement entails the knowledge change processes described for the constructive level plus an interaction with a learning partner. This interaction has specific characteristics. Both partners are required to be constructively engaged, the amount of turn-taking needs to be sufficient, and the knowledge that is generated through the exchange could not have been constructed by either of the learning partners alone but emerges from the interaction. Typical student activities for the interactive level are discussions and debates or dealing with comprehension questions.

According to the framework, the levels of cognitive engagement can be determined from observing student activities. However, this may be harder for the active, constructive, and interactive level. For example, merely observing is not sufficient in order to be sure whether the student activity is carried out on an active or constructive level. Teachers require additional information like the students' learning material and products. Critics also question whether the passive level oversimplifies deep learning processes, which can take place even when students are not actively doing something (Thurn et al., 2023). However, the ICAP framework is a heuristic to approximate the concept of cognitive engagement, and its assumptions are based on likelihoods (i.e., the likelihood that students are cognitively engaged on a passive level is higher if they are inactive; Chi & Boucher, 2023).

To simplify the process of determining whether students are engaged on an active, constructive, or interactive level, teachers may consider using technology. Technology stores the students' output and products and can therefore make the students' level of cognitive engagement visible (Henrie et al., 2015). For example, if the student activity is a

group project, aiming at interactive engagement, the teacher can suggest that the students put their contributions down in a shared document or Etherpad (i.e., a digital notebook for collaboration). This may enable teachers to determine the students' activity more precisely.

Implementing technology has shown to be effective if these technology-supported activities are cognitively engaging (Sailer et al., 2024; Stegmann, 2020): the higher the level of cognitive engagement is, the better the effects are for the learning process (Sailer et al., 2024). Especially when teaching complex skills or contents, it is beneficial to design the (technology-supported) student activities constructively and interactively. However, the ICAP framework does not propose that every student activity be constructive and interactive; instead, the appropriate level of cognitive engagement depends on the learning goal (Chi & Boucher, 2023).

The heuristic of the ICAP framework seems straightforward. However, Chi et al. (2018) found that teachers struggle with certain levels of cognitive engagement. Differentiating the active and constructive level was found to be one challenge. Additionally, teachers struggled with designing a truly interactive learning activity. This hints towards different challenges when determining the levels of cognitive engagement and, therefore, towards a variation in difficulty for the levels. Based on the presented findings and the theoretical assumptions of the framework, we assume that it is easier to determine the passive level than the other three levels. It is only at the passive level that students' overt behavior is sufficient to diagnose the level of cognitive engagement accurately. In contrast, for the active, constructive, and interactive levels, learning output, products, or materials need to be considered, too. Thus, determining these levels requires an inferential process: the level of cognitive engagement is inferred from (a) observing the student activity and (b) analyzing additional materials. However, whether the inferential process makes these levels more difficult to determine and which other factors (e.g., the teaching phase) influence the degree of difficulty of determining the levels of cognitive engagement have not yet been systematically researched. Consequently, evidence regarding which characteristics make levels of cognitive engagement difficult needs to be generated. This evidence has the potential to inform us about the levels of cognitive engagement for which teachers need additional training and technology support.

1.3. Simulation-Based Learning Environments

Diagnosing levels of cognitive engagement is very complex. Fortunately, simulation-based learning has shown to be effective for acquiring complex skills (Cook, 2014) such as technology-related diagnostic skills. Simulations can reduce the complexity of a real teaching practice while at the same time offering a platform for practicing on authentic material (Chernikova et al., 2020). A gradual approximation of practice can be achieved by dividing practice situations into subelements and then adding more elements to increase the complexity (Grossman et al., 2009). Integrating simulations into the predominantly theoretical teacher education programs may be beneficial, as simulations allow for the gradual movement from theory into the practical situation (Chernikova et al., 2020; Heitzmann et al., 2019; Machts et al., 2024). The reduced complexity is one characteristic of simulations with only a segment of reality being depicted (Chernikova et al., 2020). Another key characteristic of simulations, suggested by Heitzmann et al. (2019), is the students' opportunity to interact with the simulation. To make sure that a simulation actually fosters the skills that it is supposed to enhance, it needs to be validated (i.e., ensuring that the simulation in the form of an assessment tool measures the skills that it is supposed to). For this, researchers gather evidence that supports a convincing case for the interpretation of the outcome data (M. Kane et al., 1999). In the present study, the assumption that participants with more prior knowledge perform better in the simulation (i.e., diagnose more accurately) than

participants with lower prior knowledge is the validation criterion (Kane, 2006; Weise et al., 2020). Once simulations have successfully been validated, data from the validation study can be used to gain insights into participants' patterns within the simulation. Based on these insights, the simulation can then be turned into a learning environment.

2. The Present Study on Diagnosing Cognitive Engagement Within a Simulation

Since planning and implementing technology-supported lessons in a cognitively engaging way supports students' learning processes (Sailer et al., 2024), teachers need relevant skills to achieve this. To foster these, we created the simulation *Digivate*. With this study, we aim at validating *Digivate* and at gaining a deeper understanding of the ICAP framework. We validate the simulation *Digivate* by investigating whether higher prior knowledge is predictive of higher performance within the simulation (RQ1). We also address the lack of systematic research concerning the difficulty of diagnosing different levels of cognitive engagement (i.e., with and without inferential processes) within the planning and implementation phase (RQ2). To generate the respective evidence, we investigate which characteristics of the levels of cognitive engagement lead to challenges in the diagnostic process. Therefore, we investigate the differences in the levels of cognitive engagement (RQ2). We assume that this evidence provides us with insights into efficient ways to support acquiring technology-supported diagnostic skills regarding cognitive engagement.

RQ1. To what extent does pre-service teachers' prior knowledge predict their technology-related diagnostic skills regarding cognitive engagement within a simulation?

H1. *We hypothesize that higher prior knowledge is predictive of higher performance in technology-related diagnostic skills (i.e., a positive relation between prior conceptual knowledge and performance in the simulation).*

RQ2. To what extent does the difficulty of diagnosing levels of cognitive engagement depend on differences in the levels of cognitive engagement (inferring vs. no inferring) within the phases of teaching (i.e., planning phase, implementation phase)?

H2a. *We hypothesize that levels of cognitive engagement with no need of inferring (passive) are easier to distinguish than levels that require inferring (active, constructive, interactive; Chi et al., 2018).*

H2b. *We hypothesize that the difficulty of diagnosing the levels of cognitive engagement is different in the planning and the implementation phase (Ertmer & Ottenbreit-Leftwich, 2010).*

3. Materials and Methods

3.1. Sample and Design of the Present Study

We conducted an observational study with a correlational design as a computer-based online simulation. As there was no intervention integrated, all participants took part under the same conditions. However, the cases presented in this study were allocated to the participants in a randomized sequence. Data were collected between August 2022 and February 2023. The target group consisted of pre-service teachers, who we recruited mostly through advertising in courses at university. Participants were also given the opportunity to receive monetary compensation for completing the online study. Our sample was non-representative. The total sample included $N = 274$ pre-service teachers. We excluded participants who did not complete the whole study and reached a final sample of $n = 213$ pre-service teachers. In this final sample, 76% of the participants stated that they

were female, 22% male, 1% diverse, and 1% did not specify their gender. On average, the participants reported a teaching experience of almost five months ($M = 4.69$; $SD = 6.27$). While there are certain obligations regarding internships in the participants' study programs in the federal state of Bavaria, the number of lessons that are actually taught varies for every individual, with high flexibility as to how the teaching experience is gained. Therefore, we cannot make a statement as to where the reported teaching experience originates from. In total, 45.5% of the participants stated that they were unfamiliar with the ICAP framework, and 84% reported to never have used the ICAP framework before.

3.2. Learning Environment and Learner Task

For our study, we developed the simulation-based learning environment *Digivate*, which we designed as a point-and-click adventure. The setting of the simulation is a secondary school. At this school, teacher trainees complete their apprenticeship to become teachers. The school is currently dedicating one week to the topic of sustainability. The fictive seminar teacher, Klara Sinn, introduces the teacher trainees to this setting. She explains that they will first look at existing lesson plans and analyze the potential level of cognitive engagement of learning goals and tasks (planning phase) and then visit a class (implementation phase). In the classroom, the teacher trainees (i.e., study participants) will assess the students' level of cognitive engagement while the students are working on their tasks. Before diagnosing the levels of cognitive engagement, participants are offered to watch an introductory video on the ICAP framework. Watching the video was voluntary, as we know the ICAP framework to be part of one course within the teacher education program. With our participants studying in various semesters, we assumed differences in prior knowledge regarding the framework. To avoid redundancy, we decided on a voluntary input but urged participants to watch the video if they had not taken part in said course.

The simulation is divided into two main parts: the planning phase (see Figure 1) and the implementation phase (see Figure 2). In both phases, participants work on cases. Cases in the simulation consist of either diagnosing one lesson plan or one student activity. Cases in both the planning and the implementation phase were randomly picked and allocated to the participants out of a total of 15 cases. In the *planning phase*, a case consists of a lesson plan (i.e., learning goal, task, social grouping, and media) for which the potential level of cognitive engagement of the learning goal and the task are to be diagnosed (see Figure 1). A case in the *implementation phase* is designed as follows: First, a picture of the classroom with students sitting at desks is shown. One of the students has a colored square around their head. Clicking on this square directs the participant to the screen-video depicting what this student is currently doing on their screen (see Figure 2). The product that results from the activity in the video is shown on the next slide. Based on this input, participants choose at which level of cognitive engagement the student is currently engaged. In the sidebar, the screen-video, the learning product, the corresponding lesson plan with its desired levels of cognitive engagement for the learning goals, and the ICAP framework slides can be accessed for further support.

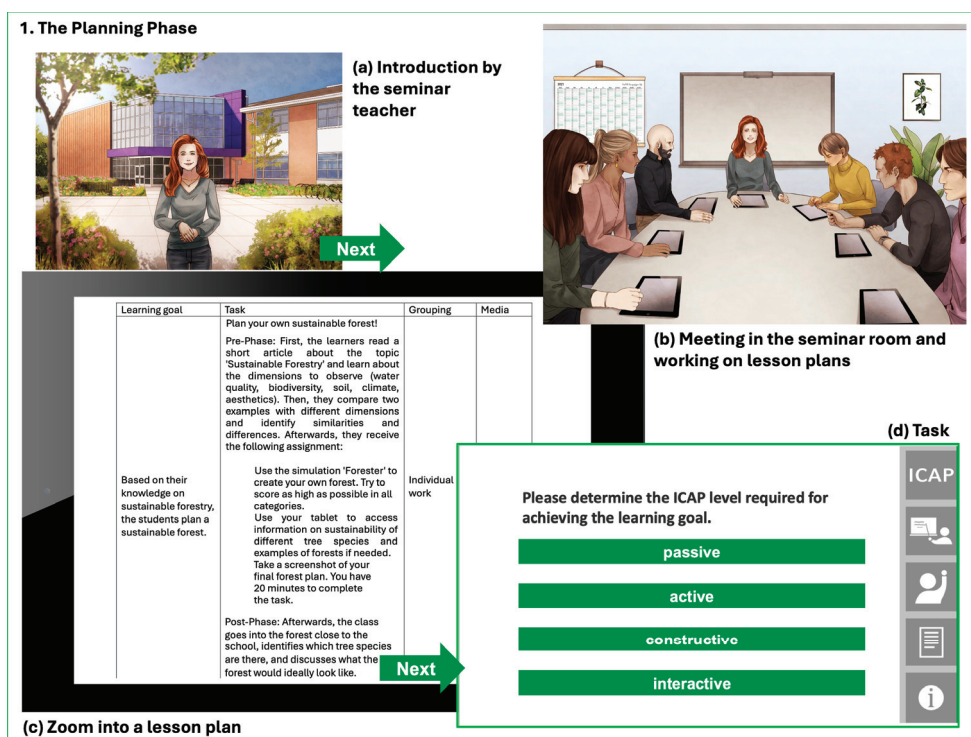


Figure 1. Overview of the structure of the planning phase.

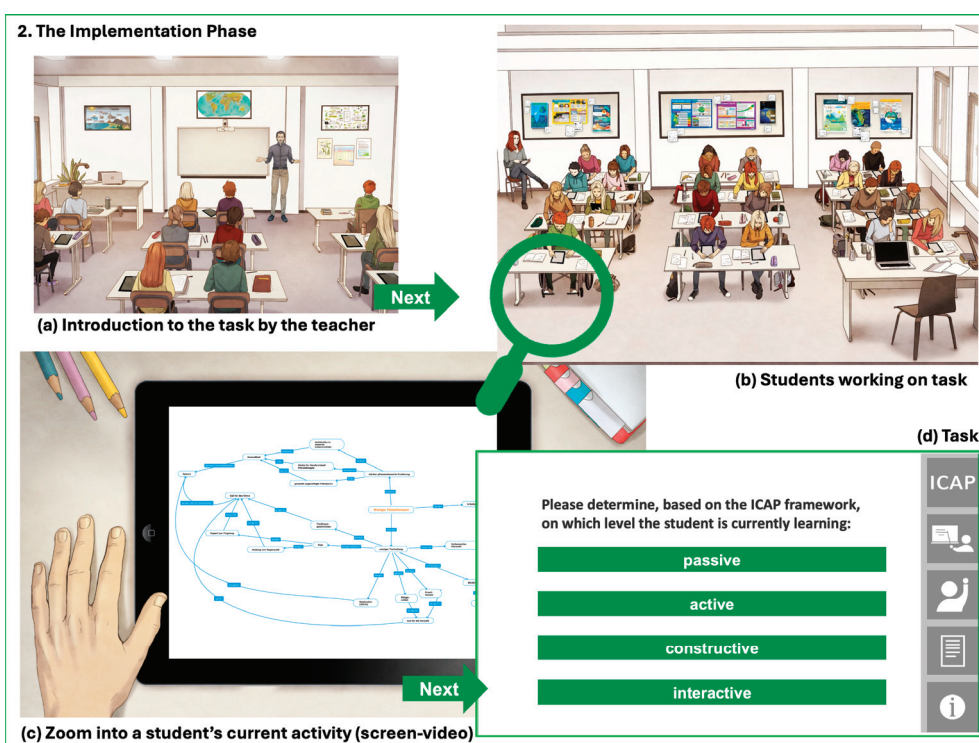


Figure 2. Overview of the structure of the implementation phase.

After completing the first case of the planning phase, the participants were assessed on their prior knowledge on cognitive engagement. They were not provided with any elements for assistance during the test. Having completed the test, the participants worked on the remaining six cases of the planning phase. After completing all cases of the planning phase, the participants found themselves back with the seminar teacher, who showed them the solution to all the lesson plans. In the next step, the seminar teacher informed

the participants that they would now see how the lesson plans were implemented in a classroom. For this implementation phase, the participants found themselves in a simulated classroom with a teacher and students (see Figure 2). The teacher introduced the teacher trainees to the class and then showed their students their next task. The study participants were instructed to walk around and determine the students' level of cognitive engagement. In total, participants worked on six cases in the implementation phase.

3.3. Measures Within the Present Study

We assessed prior knowledge with a single-choice test on conceptual knowledge on cognitive engagement. Within the simulation, we determined technology-related diagnostic skills by assessing the diagnostic accuracy.

(1) Prior Knowledge

We assessed the prior knowledge with eight single-choice items on domain-specific (Süß & Kretzschmar, 2018) *conceptual* knowledge of cognitive engagement that we designed ourselves. The test shows acceptable reliability (McDonald's Omega $\omega = .69$; Stadler et al., 2021). Each item offered four possible answers. The test included items like "In which of the four learning activities according to the ICAP framework, no product is produced?".

(2) Technology-Related Diagnostic Skills (Diagnostic Accuracy)

To measure technology-related diagnostic skills, we assessed the participants' performance in the simulation. The performance was measured by diagnostic accuracy (i.e., the sum of correctly identified levels of cognitive engagement in single-choice items; Braun et al., 2017; Hege et al., 2018). Items included the following tasks: "Please assess which ICAP level is necessary for achieving the learning goal."; "Please assess which ICAP level is necessary for achieving the learning task."; and "Based on the ICAP framework, please assess, on which ICAP level the student is learning right now". For each single-choice item, participants could achieve zero or one points. Thus, a maximum of two points per case could be gained in the planning phase and a maximum of one point in the implementation phase. In contrast to the *conceptual* knowledge that was assessed by the single-choice test (i.e., prior knowledge), we assessed the technology-related diagnostic skills through participants *applying* their knowledge (i.e., *action-oriented* knowledge) on cognitive engagement (Kopp et al., 2008). Thus, participants did not only need to know the levels of cognitive engagement and their characteristics but had to apply and transfer this knowledge in order to diagnose the simulated cases.

(3) Levels of Cognitive Engagement

The levels of cognitive engagement were represented by the levels of the ICAP framework (passive, active, constructive, interactive). The accurate levels of cognitive engagement for each learning goal, task, and student activity were validated in an expert workshop. We differentiated between levels of cognitive engagement that require inferential processes (active, constructive, interactive) and levels of cognitive engagement that do not require inferring (passive). We also differentiated between the levels of cognitive engagement in the planning phase and the levels of cognitive engagement in the implementation phase.

(4) Difficulty of Diagnosing Levels of Cognitive Engagement

We operationalized the difficulty of diagnosing cognitive engagement with sensitivity and specificity. Sensitivity and specificity can be calculated with the help of confusion matrices. Confusion matrices compare the accurate answer (predicted level) with the selected answer of participants (actual level). Sensitivity and specificity indicate which levels of cognitive engagement are more challenging to determine. Sensitivity is the proportion of true positive values to all other answers for this predicted level. Sensitivity

describes how effectively a test correctly identifies the correct answer. Specificity is the proportion of true negative values to the sum of true negative and false positive values. Specificity describes how effectively a test identifies the inaccurate answers as inaccurate.

3.4. Statistical Analyses to Address the Research Questions of the Present Study

To address RQ1, we conducted linear regression analyses, investigating whether higher prior knowledge is predictive of higher technology-related skills.

To address RQ2, we used confusion matrices to measure the difficulty of diagnosing cognitive engagement. Confusion matrices are matrices comparing predicted values (columns) with the actual values (rows). If participants correctly chose (actual level) the accurate level of cognitive engagement (predicted level), this was a true positive value (TP). If they chose an inaccurate level of cognitive engagement (actual level), this was a false negative value (FN). All levels of cognitive engagement that were correctly not chosen were true negative values (TNs). False positive values encompassed the wrongly selected predicted levels of cognitive engagement. For example, if active was the predicted level, if a participant chose active (actual value) although the predicted level was passive, constructive, or interactive, this level was called a false positive (FP).

We used chi-square tests to determine whether the confusion between levels of cognitive engagement was significant. For testing whether there were significant differences between sensitivities and specificities, we used confidence intervals (Wilson method). If there was no overlap of the intervals, there was a significant difference between the values.

4. Results

4.1. Prior Knowledge and Performance (RQ1)

The descriptive results (see Table 1) show that the participants have moderate to good prior knowledge and that their diagnostic accuracy (i.e., their performance in the simulation) was also moderate to good.

Table 1. Descriptive results for prior knowledge and diagnostic accuracy.

Variables	N	M	SD	Min	Max
Prior Knowledge	213	5.27	2.04	0	8
Diagnostic Accuracy	213	10.05	3.25	3	16

Linear regressions show that participants with higher prior knowledge diagnosed more accurately, with prior knowledge accounting for 21% of the variance in diagnostic accuracy ($R^2 = .21$). The standardized regression coefficient for prior knowledge of $\beta = .45$ ($S.E. = .10$; $p < .001$) indicates a moderately strong and statistically significant positive effect on the performance in the simulation. These findings support the validity claim with respect to RQ1.

4.2. Varying Difficulty Depending on the Levels of Cognitive Engagement and Phases of Teaching (RQ2)

To address RQ2, we created confusion matrices for the simulation over both phases (planning and implementation phase) and separate confusion matrices for the planning phase and the implementation phase.

Table 2 depicts the confusion matrix for the simulation overall, comparing the predicted (accurate) levels with the actual (selected by participants) levels. We will now describe each level of cognitive engagement within the confusion matrix.

Table 2. Confusion matrices for both phases of teaching: predicted vs. selected levels of cognitive engagement.

		Predicted			
		P	A	C	I
Actual	P	224 (63%)	172 (15%)	93 (7%)	6 (1%)
	A	65 (18%)	541 (48%)	316 (24%)	73 (7%)
	C	39 (11%)	253 (22%)	693 (52%)	140 (14%)
	I	28 (8%)	159 (14%)	240 (18%)	790 (78%)

The *passive* level was twice as often confused with active as with interactive. *Active* was mostly confused with constructive, followed by passive and, to a lesser extent, interactive. The *constructive* level was diagnosed accurately in more than half of the cases. The constructive level was most frequently confused with the active level, followed by the interactive and, lastly, the passive level. In the majority of cases, the *interactive* level was accurately determined, with its true positives standing out in contrast to the other levels of cognitive engagement. The interactive level was sometimes confused with the constructive level.

To sum up, Table 2 shows that active and constructive are confused with each other more frequently than any other levels are confused with each other. The 4×4 chi-square tests confirm a significant association between the active and constructive levels ($\chi^2(1) = 240.05, p < .001$) and a significant association between the constructive and interactive levels ($\chi^2(1) = 658.41, p < .001$). This indicates that levels of cognitive engagement that need to be inferred (active, constructive, interactive) are more difficult to distinguish from each other than the directly observable passive level.

Taking a look at sensitivity and specificity, the interactive level shows the highest sensitivity (see Table 3), meaning that it is very likely that the accurate level of cognitive engagement (interactive) is selected by the study participants. The second highest sensitivity can be found for passive, followed by constructive and active. Thus, for active, the likelihood that the accurate level (active) is selected correctly is relatively low. The confidence intervals (Wilson method) show that only for active (.45–.51) and constructive (.49–.54) there is no significant difference in sensitivity, as their confidence intervals overlap. This indicates that these two levels (active and constructive) are especially and similarly hard to diagnose, which partly supports our hypothesis: levels of cognitive engagement that need to be inferred are more difficult to determine. However, interactive also needs to be inferred but shows a high sensitivity.

Table 3. Sensitivity and specificity for the simulation over both phases of teaching.

	Sensitivity	Specificity
Passive	63%	92%
Active	48%	83%
Constructive	52%	83%
Interactive	78%	85%

Sensitivity describes how likely it is that participants correctly select the accurate level of cognitive engagement. However, not only does sensitivity provide us with information about the different difficulties of determining different levels of cognitive engagement, but so does specificity. Specificity is high for all four levels (see Table 3), indicating that it is highly likely that a level is determined as inaccurate when it is in fact inaccurate. A significant difference in specificity (Wilson method) can be found between passive (.91–.93) and the other three levels: active (.82–.85), constructive (.81–.84), and interactive (.84–.86).

To test hypothesis H2b, which predicts that the planning and implementation phases differ in difficulty when diagnosing levels of cognitive engagement, we looked at separate confusion matrices for the planning and the implementation phase (see Tables 4–6). We created two confusion matrices for the planning phase: one for the learning goals (see Table 4) and one for the tasks (see Table 5).

Table 4. Confusion matrix for the planning phase (learning goals): predicted vs. selected levels of cognitive engagement.

		Predicted			
		P	A	C	I
Actual	P	NA	88 (21%)	85 (14%)	1 (0%)
	A	NA	180 (44%)	172 (29%)	25 (9%)
	C	NA	109 (26%)	260 (44%)	47 (17%)
	I	NA	35 (8%)	73 (12%)	203 (74%)

Table 5. Confusion matrix for the planning phase (tasks): predicted vs. selected levels of cognitive engagement.

		Predicted			
		P	A	C	I
Actual	P	153 (59%)	50 (11%)	5 (1%)	0 (0%)
	A	46 (18%)	274 (58%)	110 (23%)	20 (7%)
	C	33 (13%)	81 (17%)	289 (60%)	42 (15%)
	I	27 (10%)	66 (14%)	79 (16%)	214 (78%)

Within the *planning phase*, participants started by diagnosing the level of cognitive engagement of the *learning goal*. None of the lesson plans included learning goals that were aimed at a passive level of cognitive engagement. As Table 4 shows, *active* was most frequently confused with constructive, followed by passive and interactive. The *constructive* level was mostly confused with the active level. *Interactive* was confused most frequently with constructive, followed by active and passive.

Table 5 depicts the confusion matrix for *tasks* (i.e., comparing the predicted levels of cognitive engagement of tasks to the selected levels by participants). The *passive* level of cognitive engagement was mostly determined accurately. The *active* level was slightly more often confused with constructive than with interactive and passive. The *constructive* level was mostly confused with the active level. *Interactive* was mostly accurately diagnosed and sometimes confused with the constructive level.

To summarize, Tables 4 and 5 demonstrate that for the planning phase (learning goals and tasks), the constructive and active levels, which are both levels that need to be inferred, are most frequently confused with each other. This result was confirmed in 4×4 chi-square tests (learning goals: $\chi^2(1) = 34.09$; $p < .001$; tasks: $\chi^2(1) = 183.05$; $p < .001$), which partly supports H2a, as the active and constructive levels need to be inferred, but so does interactive, which is not confused as often in the planning phase.

Looking at the sensitivity for the planning phase (see Table 7), we found different results for learning goals and tasks. Learning goals showed a rather low sensitivity for active and constructive but a higher one for interactive. This indicates that participants struggled with correctly diagnosing the accurate levels of learning goals, in particular the active and constructive levels. In contrast to learning goals, tasks overall showed a higher sensitivity. The sensitivity for tasks was highest for interactive, followed by constructive, passive, and active. To evaluate whether the sensitivities significantly differed, we used

the Wilson method to generate confidence intervals. In the planning phase (learning goals and tasks), the confidence intervals for the sensitivities only showed significant differences in sensitivity between interactive (.68–.78; .72–.82) and the other three levels of cognitive engagement: passive (NA¹; .53–.65), active (.39–.49; .54–.63), and constructive (.40–.48; .55–.64). The confidence intervals for passive, active, and constructive overlapped, indicating no significant difference in their sensitivity within the planning phase. This suggests that the interactive level differs significantly in its difficulty compared to the other levels. Since interactive showed the highest sensitivity for learning goals and tasks, we can assume that it is significantly easier to determine an interactive level, which contradicts our assumption that all levels of cognitive engagement that need inferring are more difficult to determine.

For learning goals, the specificity of the interactive level was the highest, followed by passive, active and constructive. This indicates that it was likely that participants did, in fact, identify (select) the interactive level as inaccurate. The confidence intervals (Wilson method) for learning goals showed no significant difference in specificity between active (.74–.80) and constructive (.74–.80) and for passive (.84–.88) and interactive (.87–.91), as the confidence intervals overlapped. The confidence interval of interactive (.87–.91) did not overlap. For tasks, passive showed the highest specificity, followed by interactive, constructive, and active. For tasks, only the confidence interval for passive (.94–.97) did not overlap with the other levels (active: .80–.85; constructive: .82–.87; interactive: .84–.88), indicating a significant difference in specificity between passive and the other levels. This supports H2a, as this result proposes a lower difficulty for the passive level, a level that does not require inferential processes.

To sum up, the sensitivities of active and constructive are below the sensitivity values of the interactive level (see Table 7), and the significant results in chi-square tests indicate that within the planning phase, the active and constructive levels of cognitive engagement are most difficult to differentiate. This partly supports our H2a, as the active and constructive levels require inferential processes and are more difficult to determine. However, the results indicate that interactive, also a level that needs inferring, is rather easy to determine within the planning phase.

Table 6. Confusion matrix for the implementation phase: predicted vs. selected levels of cognitive engagement.

		Predicted			
		P	A	C	I
Actual	P	71 (73%)	34 (14%)	3 (1%)	5 (1%)
	A	19 (20%)	87 (36%)	34 (13%)	28 (6%)
	C	6 (6%)	63 (26%)	144 (54%)	51 (11%)
	I	1 (1%)	58 (24%)	88 (3%)	373 (82%)

In a third step, we looked at the confusion matrix for the *implementation phase* (see Table 6), depicting the accurate (predicted) and selected (actual) levels of cognitive engagement for student activities. The *passive* level was usually accurately diagnosed. *Active* was most often confused with constructive, closely followed by interactive, but only a few times with passive. *Constructive* was mostly confused with interactive and less so with active. The *interactive* level for tasks was rarely confused with other levels. In contrast to the planning phase, in the implementation phase, the most frequently confused levels of cognitive engagement were constructive and interactive. This was confirmed by a 4×4 chi-square test ($\chi^2(1) = 177.36, p < .001$). The sensitivities in the implementation phase were highest for the passive and interactive levels (see Table 7), indicating that these levels of

cognitive engagement were easier to diagnose accurately than the active and constructive levels. The confidence intervals (Wilson method) overlapped for the sensitivity of passive (.64–.81) and interactive (.78–.85). This indicates significant differences in difficulty for diagnosing the easier levels of passive and interactive compared to the more difficult levels of active (.30–.42) and constructive (.48–.59). Regarding specificity, that of passive was the highest; interactive showed the lowest specificity. In student activities, the differences in specificity were significant between all levels of cognitive engagement, as there was no overlap in their confidence intervals. The low specificity of interactive in contrast to its high sensitivity indicates that it is easy to determine the interactive level when students act interactively, but it is difficult to recognize that students are not engaged on an interactive level. This can also be observed in the confusion matrix for the implementation phase (see Table 6) when looking at the column for constructive. Constructive was confused with interactive 88 times, which means that student activities that represented cognitive engagement on a constructive level were inaccurately diagnosed as interactive 88 times. Cognitive engagement on a constructive level involves generating knowledge on one's own, while cognitive engagement on an interactive level involves generating knowledge with others. Thus, the low specificity of the interactive level and the frequent confusing of constructive with interactive might lead to the conclusion that participants diagnosed an interactive level because more than one person was involved in the activity although no knowledge was co-generated. The findings concerning the interactive level in the implementation phase suggest that there is another difference in difficulty between the two phases of teaching.

Table 7. Sensitivity and specificity for planning and implementation phase.

	Planning Phase				Implementation Phase	
	Learning Goal		Task		Student Activity	
	Sensitivity	Specificity	Sensitivity	Specificity	Sensitivity	Specificity
Passive	NA	86%	59%	96%	73%	96%
Active	44%	77%	58%	83%	36%	90%
Constructive	44%	77%	60%	84%	54%	85%
Interactive	74%	89%	78%	86%	82%	76%

5. Discussion

5.1. Summary of the Results

With the present study, we aimed at gaining insights regarding ways to support pre-service teachers in acquiring technology-related diagnostic skills. For this, we validated the simulation Digivate (RQ1). Moreover, we systematically investigated the difficulty of levels of cognitive engagement that require inferential processes and those that do not require them within two phases of teaching (i.e., the planning phase and implementation phase; RQ2).

With respect to RQ1, we found that prior knowledge is predictive of performance in technology-related diagnostic skills. This result is in support of H1 and, therefore, our validity claim. With respect to RQ2 (i.e., investigating the difficulty of assessing the different levels of cognitive engagement), we found that active and constructive levels of cognitive engagement, as well as constructive and interactive levels, are difficult to distinguish from each other and therefore are difficult to determine. This supports H2a, which posits that levels of cognitive engagement that do not need to be inferred are easier to determine than those that need to be inferred. Moreover, H2b (i.e., different diagnostic difficulties in the phases of teaching) is also supported, as the confusion of active and constructive occurred

in the planning and the confusion of constructive and interactive in the implementation phase. Another indication is that for learning goals (planning phase), it was not only difficult to determine the accurate active and constructive level of cognitive engagement as being accurate. For learning goals, it was also difficult to identify inaccurate active and constructive levels as being inaccurate.

5.2. Practical and Theoretical Implications of the Results

From the results, we can derive implications (a) for supporting the acquisition of technology-related diagnostic skills and (b) for the design of teacher education programs at universities. For (a), based on finding the simulation to be valid and further findings about its specific difficulties for participants, we can draw conclusions towards the way in which the acquisition of technology-related diagnostic skills could be supported more effectively and, thus, how we could redesign our simulation and turn it into a learning environment. Our findings concerning the frequent confusion of the active and constructive levels align with what Chi et al. (2018) found: instead of inspecting the content of students' products, teachers took the product itself as an indicator of knowledge generation and therefore diagnosed a constructive level. Whether knowledge was generated is, however, the main difference between active and constructive. It is important to know that pre-service teachers struggle with diagnosing knowledge generation to be able to support their understanding of the knowledge generation process. This lack of understanding could, for example, be tackled by incorporating elaborate feedback on their diagnostic decisions. In the implementation phase, participants tended to diagnose that students were interactively engaged when they were in fact constructively engaged. This finding shows that it was difficult for participants to recognize an inaccurate interactive level as being inaccurate but not to determine an accurate interactive level correctly as accurate. Cognitive engagement on an interactive level implies that knowledge is co-generated through students combining their contributions. However, it may be difficult to decide in a conversation if every student generates knowledge on their own (constructive) or through co-construction (interactive). Determining whether knowledge is generated alone or together might be easier in lesson plans. Lesson plans include learning goals and tasks, and both usually describe the intended activity in detail. In contrast, screen-videos of students' activities may only depict this important aspect of the interactive level implicitly. For example, in the implementation phase, several students may talk to each other about the design of a sustainable forest, and new knowledge is generated. However, if each student comes up with their own combination of trees, the knowledge is not generated in the process, but each student generates knowledge independently and shares it with the other students. Participants working on the simulation in the present study seemed to overgeneralize the obvious feature of more than one person being involved in the implementation phase, as they frequently confused the constructive and interactive levels. Simulations offer valuable features to confront this overgeneralization of the more-than-one-person-being-involved characteristic as they bear the possibility to manipulate details of simulated cases. For example, one simulated case could represent an activity that involves several people. While this can be kept constant, the way in which they interact can be repeatedly manipulated. This way, accurately distinguishing constructive from interactive levels of cognitive engagement can be explicitly trained, as well as facilitated. This way, covert cognitive processes such as knowledge (co-)generation can be made salient within a simulation. This enables pre-service teachers to practice inferring these processes and increases the likelihood of being able to apply these inferential skills when finally standing in a classroom.

When analyzing differences between the difficulty in diagnosing levels of cognitive engagement between the planning and the implementation phase (RQ2), we found different results for the two components (i.e., learning goals and tasks) of the planning phase. For learning goals, it was more difficult to determine the accurate level of cognitive engagement as accurate (i.e., low sensitivity) than it was for tasks. In the implementation phase, similarly to tasks in the planning phase, it was easier to determine accurate levels as accurate (i.e., high sensitivity) compared to determining learning goals. This hints towards challenges when combining learning goals and the ICAP framework. The ICAP framework assumes that the level of cognitive engagement can be determined either from merely observing a student's overt behavior or from additionally taking learning products into account. The screen-videos in the implementation phase align closely with the descriptions of the levels of cognitive engagement that were proposed by Chi et al. (2018), and so do tasks to a certain extent. Tasks describe the activity in detail and report on the products that are supposed to emerge. In contrast, learning goals describe an indicator that a certain skill has been acquired. Therefore, the inferential process necessary to determine a learning goal seems more demanding, as neither an activity nor a product can be directly observed or assumed. One idea to reduce this high level of difficulty might be to suggest certain verbs that are typically used for learning goals and categorize them according to the levels of cognitive engagement, similarly to the directive verbs that Chi and Boucher (2023) proposed. Another aspect that might cause challenges with learning goals but also overall is the simplicity of the ICAP framework. With its clearly separated four levels, the ICAP framework works with categories and leaves little room for a more fine-grained differentiation. This would be possible if the levels were seen as dimensions instead of categories (Wekerle et al., 2024). Some learning goals, tasks, or student activities may be more centered within the dimension of one level than others. Possibly, typical learning goals, tasks, or student activities which are in the center of a certain level may be easier to diagnose than those that are close to the border of other levels. Thus, a suggestion to advance the ICAP framework would be to add more fine-grained levels of cognitive engagement (Wekerle et al., 2024).

In contrast to learning goals, the screen-videos representing students' activities depicted the levels of cognitive engagement more directly, as technology was used to make cognitive engagement visible to the teacher (i.e., study participant). For example, they may have observed a group of students working on a task using Etherpad (a collaborative synchronous writing tool), generating knowledge during this process. Through this observation, the advantage of the tool Etherpad for fostering cognitive engagement and, therefore, for the learning process becomes visible to the participants. The study participants would not be able to identify the level of cognitive engagement as easily without the Etherpad, making the cognitive processes visible. In contrast to complex analog group work, technology can depict relevant aspects like turn-taking or the contributing author in a shared document. To be able to diagnose the cognitive engagement of students based on the screen-videos, participants need to combine their PK (diagnosing cognitive engagement) and TK (observing students who are using technology). In the simulation, we showed how technology can be used to support cognitive engagement among students (Wekerle et al., 2024) and how teachers can use technology to diagnose their students' level of cognitive engagement. This way, we aimed to foster the study participants' TPK and, therefore, to foster their technology-related teaching skills.

For (b), implications towards the design of teacher education programs at university, we suggest that more focus and awareness should be put towards how high-level cognitive engagement can be achieved. For example, it seems to be a challenge for pre-service teachers to understand what a knowledge generation process is. Therefore, we should offer more practice opportunities to pre-service teachers, enabling them to move beyond teaching

at the active and passive levels (Sailer et al., 2024). There is also a need for sensitizing pre-service teachers towards the challenges of designing group work. By referring to the interactive level, clear criteria of what makes these types of exchanges beneficial for learning (i.e., every student is constructively engaged, sufficient amount of turn-taking) can be presented and applied (Chi & Wylie, 2014). However, it is also an opportunity to show that not every student is supposed to reach the interactive level all the time when collaborating. To acquire those skills, methods that are close to professional practice, like simulations, have significant potential (Chernikova et al., 2020). Teaching methods like simulations may also reduce the amount of passive learning activities in teacher education and support formative assessment (Black & Wiliam, 2009).

5.3. Limitations Within the Present Study

We assessed the prior knowledge using a pre-test on conceptual knowledge of cognitive engagement (i.e., the ICAP framework). The merely moderate reliability of this test may suggest considering our results with caution. However, we argue that cognitive engagement is a latent construct. As items of latent constructs are supposed to depict various aspects of the construct, a moderate reliability is justified (Stadler et al., 2021).

Another limitation is that, so far, we only included pre-service teachers as participants. Future studies may include even more heterogeneous groups of participants (e.g., in-service teachers vs. pre-service teachers) to validate the scope of participants who are likely to benefit from learning by using the simulation.

As during our study, COVID-19 restrictions were still in place, we were not able to conduct a laboratory study but merely a standardized online study. This reduced the possibilities for controlling for additional variables. Although the statistics indicate that our data are sufficient to be used to address the research questions, the study may be replicated under more controlled conditions. This way, we can ensure the quality of the data more proficiently, since we assume that participants are less likely to be interrupted or pause when working on the simulation in laboratory conditions.

Moreover, although interaction of the study participants with the simulation is a key characteristic of simulations (Heitzmann et al., 2019), for the validation, the interaction possibilities of the simulation were significantly restricted. Participants were guided through the simulation on a predetermined pathway without the possibility to repeat and practice or further explore. This decision resulted from our validation criterion, as we wanted to investigate whether prior knowledge is predictive of the performance in the simulation. In a future study, it would be interesting to explore whether comparable results occur with more degrees of freedom for the participants to interact and choose different paths within the simulation.

The present study contributed to advancing the ICAP framework. The proposed changes, however, indicate limitations in the framework. First, the ICAP framework is very focused on the implementation phase of teaching, making it challenging to evaluate learning goals based on its proposed levels of cognitive engagement. In addition, each level of cognitive engagement is rather wide (Wekerle et al., 2024). More fine-grained levels may reduce the diagnostic difficulty, make learning goals more feasible within the ICAP framework, and reduce the proposed hierarchy of the levels. Lastly, although the framework suggests that levels of cognitive engagement can be determined based on the observable student activities, this is challenging when it comes to the active, constructive, and interactive levels. These levels involve covert cognitive processes requiring inferring. To practice this, simulation-based learning seems to be an effective and efficient extension to teacher education programs.

6. Conclusions

We conclude that the simulation is sufficiently valid to be used as a learning environment for pre-service teachers in higher education. We also conclude that models of cognitive engagement in technology-supported lessons (e.g., the ICAP framework; Chi & Wylie, 2014) are, in principle, relevant and helpful for supporting pre-service teachers in learning to plan and implement technology-supported instruction for their classroom. However, these models need to be revised as well.

Findings like challenges regarding the process of (co-)generating knowledge, diagnosing learning goals, or the lack of fine-grained levels (Wekerle et al., 2024) provide insights regarding the design of an updated, adaptive version of the simulation (Plass & Pawar, 2020). Regarding the difficulty of inferring levels of cognitive engagement, scaffolds could support pre-service teachers (Belland et al., 2017). This could be achieved by making the covert learning processes more salient (Machts et al., 2024). For example, the knowledge generation can be made more visible by highlighting important aspects in the screen-videos or by adding written descriptions that make the processes more explicit. To practice the skills of accurately diagnosing the interactive level, similar cases, each involving more than one student, that systematically discriminate the level of cognitive engagement between constructive and interactive can be used. Additionally, support for diagnosing learning goals is needed. An updated simulation may also include more degrees of freedom (Heitzmann et al., 2019) and possibilities for self-regulated learning (Bannert, 2009). Such an updated version of Digivate can be implemented in teacher education as a formative assessment. This training opportunity may foster pre-service teachers' skills and awareness regarding the benefits that come with cognitively engaging their students, which will hopefully result in them planning and carrying out lessons beyond the passive and active levels of cognitive engagement.

However, not only pre-service teachers benefit from such a learning environment, but also in-service teachers. Thus, implementing the learning environment is important in all three phases of teacher education (i.e., in the first phase at university, in the second phase during practical teacher training, and for in-service teacher trainings).

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Institutional Review Board Statement: An ethical review was not required for the present study, as it was purely observational and did not involve any experimental intervention or manipulation. Participation was entirely voluntary, and no risks, harm, or disadvantages were associated with the study. No sensitive personal data were collected, and any identifying information was stored separately from the study data to ensure anonymity.

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

Data Availability Statement: The data presented in this study are available on request from the corresponding author, as we plan on further studies based on this data set.

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Notes

- ¹ The lesson plans did not include learning goals that aimed at generating a potential cognitive engagement at the passive level.

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Article

Exploring the Interplay Between Teaching Strategies and Digital Competencies Beliefs Among Pre-Service Teachers: A Longitudinal Study

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Abstract: One goal of teacher education is to create learning environments where pre-service teachers can explore and enhance their digital competencies. We aim to contribute knowledge on how these learning environments should be designed. First, our study focuses on examining the changes in pre-service teachers' Technological Pedagogical Knowledge (TPK) and Technological Pedagogical Content Knowledge (TPACK) over one semester. Secondly, we evaluate the impact of various teaching strategies aimed at fostering these professional digital competencies, as conceptualized by the Synthesis of Qualitative Evidence (SQD) model. Our sample comprised 308 pre-service teachers (30% male students; $\bar{x}_{\text{age}} = 23.29$) from one German University attending different seminars ($N = 40$). Utilizing latent-change score models and bi-factor exploratory structural equation models, we indicated no significant overall change in TPK and TPACK across seminars. Taking into account the SQD teaching strategies and students' satisfaction with these, not single teaching strategies but the orchestration of these strategies significantly positively impacted the development of pre-service teachers' TPK and TPACK across seminars within a semester. These findings highlight the importance of employing various teaching strategies in pre-service teacher education to enhance pre-service teachers' TPK and TPACK.

Keywords: digital competence beliefs; teacher education; TPACK; instructional quality; bi-factor structural equation models; longitudinal study

1. Introduction

Digital competence in the context of teachers can be defined as knowledge, motivational beliefs and situation-specific skills relevant for using information and communication technology (ICT) professionally with focus on pedagogical and didactical standards with particular focus on performance in the classroom [1,2]. One goal of teacher education programs is to develop and train pre-service teachers' professional digital competencies to meet the demands of the current and future responsibilities and challenges of their profession [3]. However, empirical studies underscore the pressing need for enhanced professional digital competencies among pre-service teachers in teacher education programs, revealing their current deficiencies in ICT knowledge and skills [4] and their lower digital competence beliefs compared to students in other fields of study [5,6]. Several studies investigate the efficacy of programs that aim to develop pre-service teachers' professional digital competencies [7,8]. Still, the empirical knowledge on specific strategies that help foster such competencies in university classes is lacking [6,9]. With a focus on the Synthesis of Qualitative Evidence (SQD) model [10], this study aims to gain such knowledge and investigate the extent to how the proposed SQD teaching strategies influence the development of pre-service teachers' professional digital competence. Guided by the Technological Pedagogical Content Knowledge (TPACK) model [11], we investigate motivational beliefs as one element of professional digital competence.

2. Theoretical and Empirical Background

2.1. Teachers' Digital Competence

There are numerous definitions of competence (see [12–14]). For the purpose of this paper, we define competence as a construct consisting of knowledge, motivational beliefs, and situation-specific skills needed to solve problems in various situations, which manifest in performance [15,16]. Digital competence is one significant competence for teacher [17] with different definitions of the construct itself (see [2]). As stated, digital competencies can be separated into basic and profession-specific areas [18–21]. Basic digital competence refers to general tasks in a media-dominated digitalized world as a citizen, whereas professional digital competence concentrates on context and domains of work-related tasks [2]. However, there are different assumptions about the relation between basic and professional digital competence, assuming that basic digital competence is integrated into professional competence or fungates as a prerequisite for teachers to enhance their professional digital competence [2,22].

In this paper, (pre-service) teachers' professional digital competence is defined as a separate factor that is interrelated with and influenced by basic digital competence [2]. Various frameworks define professional digital competence in more detail distinguishing different competence dimensions such as organization and administration, assessment or teaching, and learning [23,24]. Another well-established theoretical concept of professional competencies among teachers to use ICT is the TPACK model [11]. Based on Shulman's [25] model of content and pedagogical knowledge, the TPACK model evolved with the supplement of technological knowledge [11] and focuses on the interrelationship among knowledge in the field of technology (TK), pedagogy (PK), and content (CK) with four sub-components: Technological Content Knowledge (TCK), Pedagogical Content Knowledge (PCK), Technological Pedagogical Knowledge (TPK) and Technological Pedagogical Content Knowledge (TPACK). TCK pertains to understanding the reciprocal relationship between ICT and content, while PCK encompasses the organization and adaptation of subject matter for instruction [26]. TPK involves recognizing how ICT can influence pedagogical practices, and TPACK integrates knowledge of these interactions to develop effective teaching strategies tailored to specific contexts [26]. Emphasizing the importance of content, the TPACK model focuses especially on the use of ICT for didactic purposes in teaching. Technological or digital knowledge (DPACK) [27] is defined as a prerequisite for the effective integration of ICT, which fits the definition of teachers' digital competence by Rubach & Lazarides [2], i.e., that basic digital competence (equivalent to the TK component) is a prerequisite of their professional competence [2]. The TPACK model underlines the importance of knowledge. However, scholars often used surveys asking for (pre-service) teachers' perceived skills or knowledge rather than actual knowledge tests to operationalize TPACK and its sub-components [21]. Thus, empirical studies often state that teachers with strong competence-related beliefs in TPACK are capable of integrating ICT into their classes by considering the pedagogical goals and content when choosing ICT for teaching [28,29].

2.2. What It Needs to Enhance Pre-Service Teachers' Professional Digital Competencies

The development of competencies necessitates learning experiences provided and offered to pre-service teachers during their academic studies. Hense and Goertz [30] found that nearly 70% of the students would like to have a more interactive and multimedia-based learning experience and perceive it as positive if more digital teaching content were used in their studies. These findings underline the importance of integrating ICT and training of ICT integration into teacher education programs to foster the development of digital competencies among future educators [6,7,31,32].

To enhance pre-service teachers' professional digital competence, Tondeur and colleagues [10] proposed the SQD model, which subsumes twelve key strategies for preparing pre-service teachers to integrate ICT in class by fostering their professional digital competence (see Figure 1).

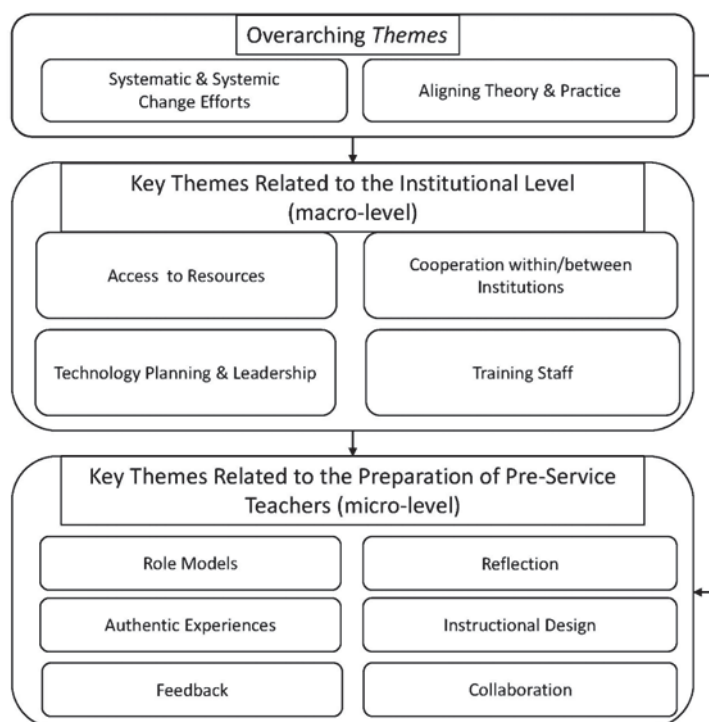


Figure 1. SQD Model based on Tondeur and Colleagues [10].

These strategies serve as a guide providing teaching strategies and thus assist educators in creating high-quality learning environments in teacher education. Six of these strategies (role models, instructional models, authentic experiences, collaboration, reflection, feedback) are directly associated with the training of pre-service teachers in class (micro-level strategies), thus providing a framework for content-specific strategies for instructional quality [10]. Role models as strategy are defined as teacher educators supporting the pre-service teachers by observational learning and modeling the use of ICT [33,34]. Instructional design provides learning experiences where future teachers learn how to use ICT for their teaching [10] and designing learning materials using ICT [33]. Authentic experiences provide pre-service teachers with opportunities to test ICT in authentic settings, for example internships and teaching simulations [35]. In other words, through authentic experience, pre-service teachers will be able to use theoretical knowledge in practical experiences. Another strategy is collaboration, where students discuss their experiences with ICT and their methods to integrate it into their teaching with peers and teachers, building a community of practice wherein participants collectively address pertinent practical challenges [33] (see [33] for more information about collaborative lesson design). The last strategies are reflection and feedback. Throughout the teacher's educational program, pre-service teachers should discuss and critically reflect upon the role of ICT after their experiences using ICT. Tondeur and colleagues [36] mention that feedback about the use of ICT is essential for the development of future teachers' professional digital competence. They distinguish between formative and summative feedback, where formative feedback refers to continuous and adequate feedback helping future teachers in their development of ICT integration in teaching. In contrast, summative feedback involves assessing pre-service teachers' digital competencies, especially those required in teaching practices [36].

Multiple scholars have investigated the extent to how the proposed strategies by the SQD model relate to pre-service teachers' professional digital competence, e.g., their self-assessed TPACK. Some studies examine the individual strategies of the SQD model [37–39], while others consolidate them into the general factor [40,41] to investigate its cross-sectional or longitudinal relation with pre-service teachers' self-assessed TPACK. Starting with cross-sectional findings, research has shown positive associations between implementing the SQD strategies into the teaching process and pre-service teachers' self-assessed

TPACK [36,37,41–44]. Many scholars demonstrated positive cross-sectional links between all the SQD strategies (as S-factors or bi-factor) and pre-service teachers' self-assessed TPACK and related components [40–42]. Some studies have investigated the extent to how the combinations of these SQD strategies impact pre-service teachers. For example, studies found different combinations of the SQD teaching strategies to be important for TPACK, i.e., reflection and instructional design [37]; reflection, collaboration, and authentic experiences [45] or authentic experiences, instructional design, and role models [38]. Recent studies highlight a particularly robust correlation of different combinations of these strategies with pre-service teachers' self-assessed TPACK. According to multiple cross-sectional studies, integrating authentic experiences, role models, and collaboration is particularly significant in this regard [40,46,47]. However, the context in which these strategies were used is important to consider: Tondeur and colleagues [44] discovered through a cross-sectional interview study that observing role models in practical experiences in school was perceived more important for the TPACK development than their experiences in teacher education seminars.

Other studies also highlighted the significance of the SQD strategies for pre-service teachers' development in their self-assessed TPACK: For example, one study reported a positive change in pre-service teachers' self-assessed TPACK in modules which were designed guided by the SQD model compared to pre-service teachers in modules lacking the SQD focus [48]. However, there was no significant difference in the pre-service teachers' self-assessed TPK between the two groups [48]. The authors discussed this finding with the general problematical understanding in instructional quality research that pre-service teachers find it challenging to transfer their subject-specific knowledge to broader pedagogical contexts, i.e., as applying their expertise in subjects like Mathematics to general teaching strategies, including classroom management or interdisciplinary teaching [48,49]. Other studies investigated pre-service teachers' self-assessed TPACK based on the SQD strategies in more detail: Da Bueno and Niess [46], for example, found that pre-service teachers develop TPACK through authentic learning experiences (e.g., teaching practice in schools) by using ICT in their teaching. Focusing on reflection as a strategy, Kramarski and Michalsky [50] indicated in an experimental pre-post-setting that pre-service teachers in groups receiving ICT instructions and engaging in reflection on ICT use had higher levels of TPACK skills compared to the group that received only instructional features without reflection as a strategy. Additionally, Hsu & Lin [37] found that instructional design for using ICT in teacher education classes is important for TPACK of pre-service teachers. Furthermore, a longitudinal study centered on TPACK, rather than the SQD strategies, examined the impact of tailored seminars on TPACK development [51]. Notably, it observed positive changes in TPACK proficiency over time. Also, a few studies investigated the extent to how TPACK components, e.g., TPK and TPACK, developed based on the use of single SQD strategies in teacher education classes at university [37,44].

In summary, multiple studies point to the significance of described SQD strategies for pre-service teachers' self-assessed TPACK [40,41]. Tondeur and colleagues [10,41,52] emphasize orchestrating the six SQD strategies in this context. However, Gümüş and colleagues [53] adjusted the model, taking into account another perspective of the SQD model, focusing on the individual strategies. This raised the following question: Is it more effective to orchestrate the SQD strategies in seminars, or do pre-service teachers need specific strategies to develop TPK and TPACK? For this study, we decided to evaluate both approaches.

Yet, there needs to be more evidence which helps to understand the importance of specific SQD strategies enhancing pre-service teachers' self-assessed TPACK and its components. Hereby, only a few studies investigated the relevance of all SQD strategies compared to each other in longitudinal real-world settings as university classes [40] rather than in quasi-experimental research designs [48]. Such knowledge, however, is highly important for teacher education. As educators of future teachers who need to prepare

pre-service teachers for the complexities of modern classrooms, understanding the factors that shape pre-service teachers' professional digital competencies becomes paramount.

2.3. The Present Study

Previous research has identified a positive link between strategies in the SQD model and pre-service teachers' self-assessed TPACK [40,41], with an increasing emphasis on discerning the most effective SQD strategies for promoting TPACK [37,44]. These investigations, predominantly cross-sectional studies, have highlighted several avenues for teacher education. Notably, there is a pressing need for longitudinal studies, particularly in real-world settings, and larger sample sizes [36,39,47,48] to assess the complex interplay among pre-service teachers' perceptions of their TPACK in the context of teaching strategies, as conceptualized by the SQD model [37]. Additionally, it is crucial to focus more broadly on aligning competency goals with the learning content, particularly examining the connection between pre-service teachers' experiences and the design of teaching during their studies to enhance teaching processes [54].

Our study built upon prior research, addressing identified limitations, and investigated the longitudinal relationships between strategies conceptualized in the SQD model [10] and pre-service teachers' self-perceived TPK and TPACK. The following research questions (RQ) and hypotheses (H) guided our investigation:

RQ1: How do pre-service teachers' self-perceived TPK develop in relation to the SQD teaching strategies?

As Lachner and colleagues [48] indicated no significant change of TPK in combination with the SQD strategies in an orchestrated manner, we assume no longitudinal link between the SQD strategies and the development of TPK (H1).

RQ2: How do pre-service teachers' self-perceived TPACK develop in relation to the SQD teaching strategies?

Drawing from previous research [43,44], we hypothesize a positive development of TPACK with the increased perception of different strategies of the SQD model in an orchestrated manner (H2a). Given the cross-sectional results, we hypothesize that the individual strategies of authentic experiences, role models, and collaboration positively influence the development of TPACK (H2b) [40,46,47].

For both research questions we will consider the orchestration and the individual SQD teaching strategies.

3. Methodology

3.1. Sample

To answer our research questions, data were drawn from the pre-registered *Skillful-Teacher2.0* project at the University of Rostock in Germany (see [55]). The goals of the project were to investigate (a) the development of various facets of digital competence of pre-service teachers, (b) the longitudinal relationships between the development of general and professional digital competence, and (c) the impact of content, methods and instructional quality dimensions in pre-service teachers' seminars on their development of various facets of digital competence. A total of 904 pre-service teachers were surveyed across two cohorts, i.e., in the summer semester 2023 ($n = 720$) and winter semester 2023/2024 ($n = 184$). The pre-service teachers who attended the participating seminars (one lecture, 40 seminars) completed three surveys: one at the semester beginning, one in the middle of the semester and one at the end of the lecture and seminars (see Figure 2). Half of the seminars ($n = 18$) served as control groups with no explicit focus on digital education and the development of digital competencies of pre-service teachers. The study followed a voluntary participation model and was fully compliant with institutional review board (IRB) standards.

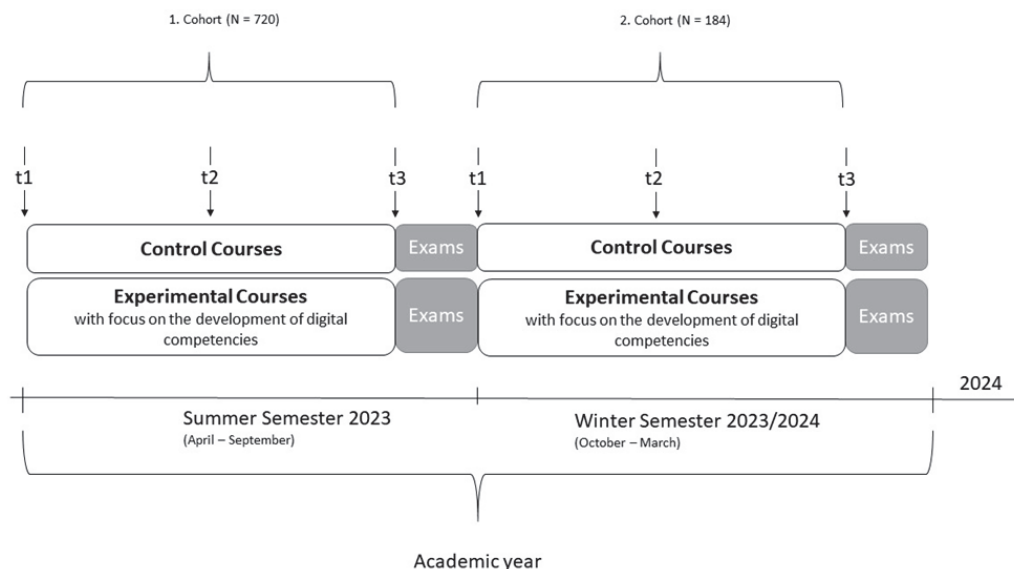


Figure 2. Design of the SkillfulTeacher2.0 Project. *Note.* T1 = first measurement point at the beginning of the semester, t2 = second measurement point in the middle of the semester, t3 = third measurement point at the end of the semester.

A subsample was analyzed for the aim of this paper. Focusing on the research questions, we only considered pre-service teachers who answered items related to SQD, TPK and TPACK. Accordingly, we used data only from the first and the last survey as they had the mandatory items included. Further restrictions were made to improve the reliability and validity of the data: as only one lecture was part of the project, only data from seminars were considered, ensuring a constant teaching context. Seminars with fewer than five participants were excluded, as were students' cases of double enrollments across the semesters. Additionally, participants from vocational pedagogy programs were excluded due to the low number of respondents. As a result of these restrictions, the final sample included data from 308 pre-service teachers (30% male students; $\bar{x}_{\text{age}} = 23.29$, $SD = 7.18$, 98% German as native language, 27 seminars). The pre-service teachers were enrolled in various K-12 teacher education programs, e.g., 34% gymnasium, 24% special education, 23% primary school, 18% secondary school, and 2% economical school. Participants ($\bar{x}_{\text{semester}} = 7$) were spread across various subjects such as 54% German language, 42% mathematics, 22% physical education, 17% biology, and 16% social studies. With the term “subject” we refer to different content disciplines, for example Mathematics and History, pre-service teachers can choose and will later teach in the classroom. More than one subject could have been chosen since teacher education in Germany involves studying several subjects simultaneously.

3.2. Instruments

All items are presented in the Supplemental Materials, part one.

Teaching Strategies Targeting to Foster Digital Competence (SQD). To examine the teaching strategies used by instructors to foster digital competence in seminars, we used the existing instrument on SQD teaching strategies developed by Tondeur and colleagues [10,52]. In their synthesis, Tondeur and colleagues [52] conducted an extensive review of the literature on effective ICT integration in teacher education and identified six key teaching strategies (see Figure 1) that are crucial for preparing pre-service teachers to effectively incorporate ICT into their future classrooms [7,40]. Building on this established framework, we adapted certain items of the SQD model to address the importance of various stakeholders, including instructors, peers, students, and teachers, when preparing pre-service teachers to integrate ICT in class [44,56,57]. For example, we embedded questions tailored to the pre-service teachers' experiences with integrating ICT working with students in K-12 (item example: “I had opportunities to try out ICT in interaction with students.”) or differentiated

between discussion about ICT use with instructors (item example: “I observed ICT use in order to integrate applications myself in my future profession as a teacher.”), peers (item example: “I have exchanged experiences with fellow students on the use of ICT for our future professional career as teachers.”), and teachers (item example: “I have exchanged experiences with teachers on the use of ICT.”). In total, pre-service teachers responded to 19 items at the end of the semester on a Likert-scale from 0 = *did not occur*, 1 = *not satisfied at all* to 7 = *completely satisfied*. Thus, we assessed pre-service teachers’ perception of teaching strategies guided by the person–environment fit approach and students’ satisfaction with their experiences [58–60]. The factors role model, reflection, collaboration, and feedback were measured by three items, the factor instructional design by two items, and the factor authentic experience by five items. As we integrated new items, we first aimed to validate the theoretically assumed structure. Results are reported in the results section.

Technological Pedagogical Knowledge (TPK). To examine the development of pre-service teachers’ self-perceived TPK [61,62], the participants responded to four items at the beginning and the end of the semester on a Likert-scale from 1 = *not competent at all* to 7 = *highly competent*. One item (TPK04) was excluded from the analysis due to poor model fit. The scales showed good reliability ($0.88 \leq \Omega \leq 0.89$).

Technological Pedagogical Content Knowledge (TPACK). To examine the development of pre-service teachers’ self-perceived TPACK [61,62], the participants responded to four items at the beginning and the end of the semester on a Likert-scale from 1 = *not competent at all* to 7 = *highly competent*. The scales showed good reliability ($0.91 \leq \Omega \leq 0.94$). The items assessed students’ self-perceived TPK and TPACK and relate to their competence beliefs in solving a particular task, and are thus theoretically guided by the expectancy-value theory [63]).

3.3. Statistical Analysis

To answer our research questions, we used *Mplus* 8.11 [64]. All specified syntaxes are presented in the Supplemental Materials, part two. Used data were clustered as pre-service teachers were grouped in seminars. Exploring the structure of our data, we conducted intraclass correlation coefficients (ICC), determining whether multilevel analyses [65] should be considered. ICC_1 and ICC_2 were calculated [66], revealing that variance in TPACK was less than 5% attributable to seminars, while for TPK, it ranged from 5% to 13%. The measurement of the ICC’s confirmed the hierarchical structure of the data (pre-service teachers nested in seminars). According to Scherer [67], there are at least two options to account for clustered data: (1) a multilevel analysis in order to explain between-level differences in the nested structure of the data, or (2) a structural equation model (SEM) approach taking the nested structure into account [68]. We chose the second option since our research interest did not focus on differences between seminars. Thus, we used the *type = complex* command to correct standard errors within clusters. The Maximum Likelihood Estimator (MLR) [64] was used as it produces reliable standard error estimates [67,69]. The model fits were investigated using the following indices and cut-offs: Comparative Fit index (CFI) and Tucker and Lewis index (TLI) values greater than 0.90, and root mean square of approximation (RMSEA) values lower than 0.08 were accepted as indicators of an acceptable model fit [70,71].

As we were interested in the extent to how the strategies conceptualized in the SQD model [10] impact pre-service teachers’ self-perceived TPK and TPACK, we conducted three analysis steps, which are described in the following.

First, we conducted two latent-change score models [72] for the constructs TPK and TPACK to show the development of both constructs from the beginning to the end of the seminars, independent of the investigated teaching strategies. Beforehand, we tested the pre-condition of latent-score models by the measurement of invariance (MI) to confirm that the latent constructs TPK and TPACK are equally measured across time [73,74]. In our analysis we used the criteria of Chen [75] for adequate sample sizes (total $N > 300$), with a change of $\Delta CFI \leq 0.010$, supplemented by a change of $\Delta RMSEA \leq 0.015$ or a change of

$\Delta\text{SRMR} \leq 0.030$ for testing loading invariance and testing intercept and residual invariance change of $\Delta\text{CFI} \leq 0.010$, supplemented by a change of $\Delta\text{RMSEA} \leq 0.015$ or a change of $\Delta\text{SRMR} \leq 0.010$ to confirm configural, metric, scalar, and strict invariance [76]. The necessity of scalar invariance for conducting latent-change score models is given [77], as the results validated strict measurement invariance over time (see Table 1). Following this, we modeled the latent change scores $((\tau_1 + (\tau_2 - \tau_1)))$ by fixing some values to 1 [72,78].

Table 1. Model Fit Indices of Tested Measurement Invariance (MI) and Latent Change Score Models (LCSM) for the Construct TPK and TPACK.

	χ^2	df	p	AIC	BIC	RMSEA	ΔRMSEA	CFI	ΔCFI	TLI	SRMR	ΔSRMR
<i>TPK Models</i>												
Configural MI	7.370	8	0.497	4512.851	4588.256	0.000	—	1.000	—	1.000	0.038	—
Metric MI	8.425	10	0.587	4509.905	4577.373	0.000	0.000	1.000	0.000	1.000	0.044	−0.006
Scalar MI	13.511	12	0.333	4510.992	4570.522	0.018	−0.018	0.999	0.001	0.998	0.052	−0.008
Residual MI	46.680	15	≤ 0.001	4538.161	4585.786	0.073	−0.055	0.969	0.030	0.969	0.146	−0.094
Partial residual MI	25.560	14	0.029	4519.041	4570.635	0.046	−0.028	0.989	0.010	0.988	0.064	−0.012
LCSM	12.220	12	0.043	3693.664	3749.469	0.008	—	1.000	—	1.000	0.048	—
<i>TPACK Models</i>												
Configural MI	148.756	19	≤ 0.001	5642.128	5741.088	0.133	—	0.937	—	0.908	0.028	—
Metric MI	152.032	22	≤ 0.001	5639.404	5726.489	0.124	0.009	0.937	0.000	0.920	0.050	−0.022
Scalar MI	165.763	25	≤ 0.001	5647.135	5722.345	0.121	0.003	0.932	0.005	0.924	0.052	−0.002
Residual MI	180.504	29	≤ 0.001	5653.876	5713.252	0.116	0.005	0.927	0.005	0.930	0.051	0.001
LCSM	46.461	23	0.003	4597.048	4675.037	0.058	—	0.982	—	0.098	0.045	—

Note. TPK = Technological Pedagogical Knowledge, TPACK = Technological Pedagogical Content Knowledge.

Second, we investigated the theoretically described structure of the SQD model with six factors using various modeling approaches, i.e., confirmatory factor analysis (CFA), exploratory structural equation model (ESEM), bi-factor SEM and bi-factor ESEM [72,79]. To interpret the various modeling approaches, model fits were compared. Utilizing these models increased the understanding of the used data. The CFA validates theoretical assumptions of the data structure, whereas the ESEM explores the structure beyond the predefined theory, i.e., allowing for set cross-loadings that define the teaching strategies as not independent. The bi-factor model thought accounts for each single teaching strategy (S-factors), revealing the impact of the orchestration of these strategies as shared variance (bi-factor) [79]. Finally, the bi-factor ESEM fitted the model best and was selected for further analysis.

Third, we specified autoregressive models [80] to further investigate the impact of the teaching strategies according to the SQD model and the development of self-perceived TPK and TPACK. Here, we used the final model from the second analysis step and modeled the development of TPK and TPACK in an autoregressive path [72]. Hereby, TPK and TPACK at the beginning of the semester (t1) were modeled as predictors of the teaching strategies (S-factors) and the bi-factor (see Figure 3). Furthermore, TPK and TPACK at the end of the seminar (t2) are predicted by TPK and TPACK at the beginning of the seminar, the bi-factor, and the different teaching strategies (S-factors).

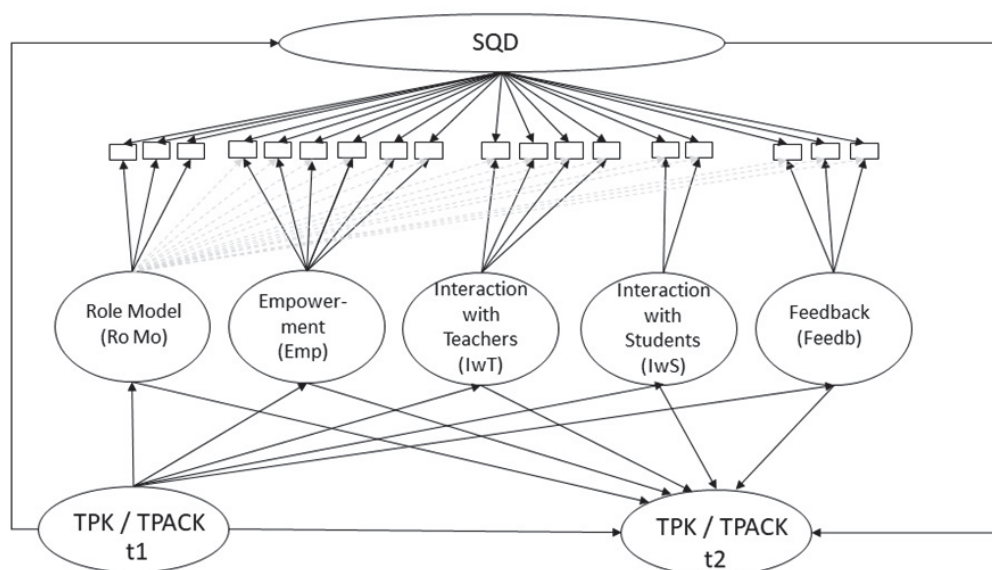


Figure 3. Analytic model. *Note.* TPK = Technological Pedagogical Knowledge, TPACK = Technological Pedagogical Content Knowledge, t1 = first measurement point at the beginning of the semester, t2 = second used measurement point at the end of the semester (was the third measurement point in the project).

4. Results

4.1. Change of TPK and TPACK

Table 1 shows the fit indices of model tested for measurement invariance (MI) and latent-change score model (LCSM) for the constructs TPK and TPACK. (Partial) residual invariance was confirmed for both constructs, indicating that we can validly compute latent change score models. To address our research aim, we estimated two LCSMs. The fits were found to be good in both models (see Table 1). There was no significant change of TPK ($\beta_{\Delta} = 0.146$, $S.E. = 0.116$, $p = 0.211$) and TPACK ($\beta_{\Delta} = 0.073$, $S.E. = 0.097$, $p = 0.454$) over time. However, the variance of both constructs indicated interindividual differences in the change (TPK: $\sigma^2_{\Delta} = 1.329$, $S.E. = 0.172$, $p \leq 0.001$; TPACK: $\sigma^2_{\Delta} = 1.139$, $S.E. = 0.159$, $p \leq 0.001$).

4.2. Structure of SQD

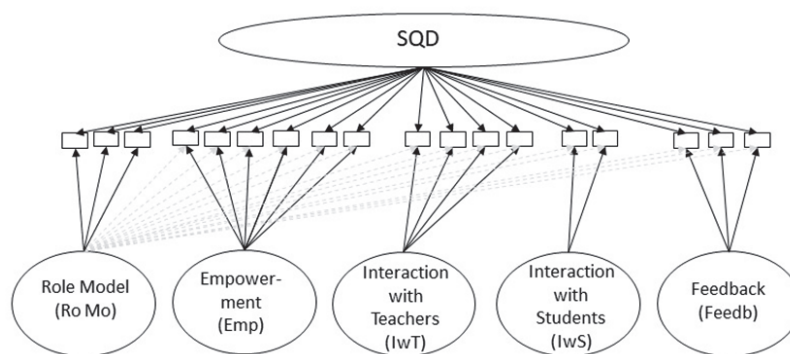
To confirm the suggested theoretical structure of the SQD model [10], we conducted a CFA. The results demonstrated that the 6-factor structure fit the data poorly (see Table 2). When using different modeling approaches, i.e., ESEM, bi-factor SEM and bi-factor ESEM model approaches, the bi-factor ESEM fit the data best (see Table 2). However, even though the model fit was good, we indicated some problems with the factors of instructional design and collaboration, as no items loaded in a sufficient way on these factors.

We, thus, performed an exploratory factor analysis (EFA) for the SQD model to further validate the structure, which then revealed a 5-factor structure (see Figure 4). Here, the factors role model and feedback were retained, but three new factors were indicated: empowerment, interaction with teachers, and interaction with students. The first factor, empowerment, compromised the original factors of collaboration, authentic experiences, and instructional design, highlighting the empowerment of pre-service teachers in university classes. The second factor, interaction with teachers, and third factor, interaction with students, are related to the discussion and collaboration with K-12 teachers and students regarding the use of ICT in classrooms.

Table 2. Model Fit Indices of Tested Models for the Construct SQD.

	χ^2	<i>df</i>	<i>p</i>	<i>AIC</i>	<i>BIC</i>	<i>RMSEA</i>	<i>CFI</i>	<i>TLI</i>	<i>SRMR</i>
<i>Model based on SQD theory</i>									
CFA (1–factor)	761.246	152	≤ 0.001	15,539.603	15,727.034	0.142	0.787	0.760	0.084
CFA (6–factors)	385.934	134	≤ 0.001	14,994.356	15,240.976	0.097	0.912	0.887	0.063
<i>Results of EFA on SQD</i>									
1–factor solution	923.938	135	≤ 0.001	14,835.653	15,013.219	0.172	0.749	0.751	0.084
2–factor solution	656.119	118	≤ 0.001	14,601.834	14,835.301	0.152	0.828	0.778	0.057
3–factor solution	440.092	102	≤ 0.001	14,417.807	14,703.886	0.129	0.892	0.838	0.039
4–factor solution	320.744	87	≤ 0.001	14,328.459	14,663.862	0.116	0.925	0.869	0.029
5–factor solution	175.810	73	≤ 0.001	14,211.525	14,592.964	0.084	0.967	0.931	0.018
6–factor solution	N. A.								
<i>Model based on EFA results</i>									
CFA (5 factors)	224.279	124	≤ 0.001	14,273.844	14,487.581	0.064	0.960	0.950	0.040
Bi-factor SEM	227.520	117	≤ 0.001	14,271.328	14,508.084	0.069	0.956	0.942	0.049
ESEM	124.165	74	0.002	14,212.443	14,590.594	0.059	0.980	0.958	0.018
Bi-factor ESEM	98.681	62	0.002	14,193.870	14,611.480	0.055	0.985	0.964	0.016

Note. CFA = Confirmatory Factor Analysis, EFA = Exploratory Factor Analysis, Bi-factor SEM = Bi-factor Structural Equation Modeling, ESEM = Exploratory Structural Equation Modeling, Bi-factor ESEM = Bi-factor Exploratory Structural Equation Modeling.

**Figure 4.** Model of the Exploratory SQD Approach.

Using the suggested structure of the EFA, we also conducted different modeling approaches. Also here, the bi-factor ESEM demonstrated the best model fit ($\chi^2 (62) = 98.68$, $CFI = 0.99$, $TLI = 0.96$, $RMSEA = 0.055$, $SRMR = 0.016$), consistent with the results from the theory-driven SQD model. This indicates that the bi-factor ESEM with five factors (for similar results see [53]) provides a more accurate representation of the data, allowing us to examine the SQD structure not only in relation to individual teaching strategies (S-factors) but also in the orchestration of all strategies (bi-factor) on the outcomes of interest, TPK and TPACK [53,81]. Factor loadings of the final bi-factor ESEM are provided in Table 3. The scales showed good reliability ($0.88 \leq \Omega \leq 0.94$).

Table 3. Standardized parameter estimates from the bi-factor ESEM solution and the item allocations.

Name	Bi-Factor (λ)	Ro Mo (λ)	Emp (λ)	IwT (λ)	IwS (λ)	Feedb (λ)
Ro Mo 1	0.739	0.428	0.031	0.033	−0.025	0.005
Ro Mo 2	0.698	0.494	0.007	−0.022	−0.163	−0.036
Ro Mo 3	0.810	0.323	0.189	−0.048	−0.079	−0.073
Emp 1	0.754	0.162	0.144	−0.022	−0.020	0.009
Emp 2	0.788	0.062	0.234	0.044	−0.039	0.158
Emp 3	0.810	−0.065	0.413	−0.078	−0.031	−0.023
Emp 4	0.796	0.150	0.260	0.012	−0.078	−0.058
Emp 5	0.788	0.017	0.503	0.031	−0.026	0.042
Emp 6	0.783	0.156	0.309	−0.043	0.085	0.046
IwT 1	0.683	0.121	−0.194	0.358	0.033	−0.149
IwT 2	0.766	−0.254	−0.283	0.409	0.024	−0.178
IwT 3	0.684	0.076	−0.004	0.389	0.165	0.138
IwT 4	0.580	0.101	0.216	0.776	0.051	0.057
IwS 1	0.566	−0.166	−0.035	0.073	0.556	0.055
IwS 2	0.584	−0.030	−0.016	0.105	0.803	0.040
Feedb 1	0.749	−0.023	0.083	0.068	0.080	0.432
Feedb 2	0.752	−0.051	0.059	−0.105	0.045	0.546
Feedb 3	0.678	−0.003	−0.047	−0.001	0.009	0.402

Note. Bi-factor = general factor; Ro Mo = Role Model; Emp = Empowerment; IwT = Interaction with Teachers; IwS = Interaction with Students; Feedb = Feedback, bold highlighted values correspond to the respective factor.

4.3. Longitudinal Links Between SQD, TPK, and TPACK

Lastly, we estimated two autoregressive bi-factor models using the bi-factor ESEM of the exploratory SQD model and the latent factors of TPK and TPACK from both measurement points. Here, we estimated (a) the effects of TPK and TPACK at the beginning of the semester on the perception of the SQD teaching strategies and (b) the effects of perceived SQD teaching strategies on the self-perceived TPK or TPACK at the end of the semester by controlling for the initial TPK and TPACK at the beginning of the semester (see Figure 3). Correlations between all estimated factors are presented in Table 4.

Table 4. Correlation of the Exploratory Approach of SQD and TPK (Model 1) and TPACK (Model 2).

Factors	Model 1						Model 2					
	TPK _{t1}			TPK _{t2}			TPACK _{t1}			TPACK _{t2}		
	<i>r</i>	<i>S.E.</i>	<i>p</i>	<i>r</i>	<i>S.E.</i>	<i>p</i>	<i>r</i>	<i>S.E.</i>	<i>p</i>	<i>r</i>	<i>S.E.</i>	<i>p</i>
Bi-factor	0.053	0.087	0.544	0.288	0.114	0.011	0.110	0.055	0.047	0.374	0.093	≤ 0.001
Ro Mo	0.049	0.083	0.552	0.130	0.085	0.126	0.022	0.156	0.886	0.105	0.113	0.355
Emp	−0.041	0.112	0.711	0.110	0.097	0.282	−0.070	0.134	0.601	0.008	0.125	0.947
IwT	0.020	0.067	0.761	0.016	0.086	0.856	0.035	0.110	0.751	0.031	0.080	0.698
IwS	−0.102	0.084	0.227	−0.013	0.082	0.871	−0.117	0.106	0.269	0.011	0.073	0.881
Feedb	0.029	0.087	0.741	−0.011	0.067	0.869	−0.102	0.110	0.355	0.077	0.079	0.334
TPK _{t1} /TPACK _{t1}	1	—	—	0.295	0.087	≤ 0.001	1	—	—	0.422	0.073	≤ 0.001
TPK _{t2} /TPACK _{t2}	0.295	0.087	≤ 0.001	1	—	—	0.422	0.073	≤ 0.001	1	—	—

Note. TPK = Technological Pedagogical Knowledge, TPACK = Technological Pedagogical Content Knowledge, t1 = first measurement point at the beginning of the semester, t2 = second measurement point at the end of the semester, Bi-factor = General factor of SQD; Ro Mo = S-factor for Role Model; Emp = S-factor for Empowerment; IwT = S-factor for Interaction with Teachers; IwS = S-factor for Interaction with Students; Feedb = S-factor for Feedback, bold highlighted values are significant ($p \leq 0.05$).

Results on TPK. The final results are presented in Figure 5. The model demonstrated good model fits: $\chi^2(170) = 224.171$, CFI = 0.985, TLI = 0.975, RMSEA = 0.032, SRMR = 0.030. First, the initial TPK (t1) was not related to later perceived SQD teaching strategies. Second, initial TPK (t1) predicted later TPK (t2). Third, self-perceived TPK (t2) was positively predicated by the bi-factor of SQD while controlling for TPK at the beginning of the semester (t1) (H1). No meaningful effect was found for the S-factor with one exception of a marginal significant effect from the factor role model on TPK (t2).

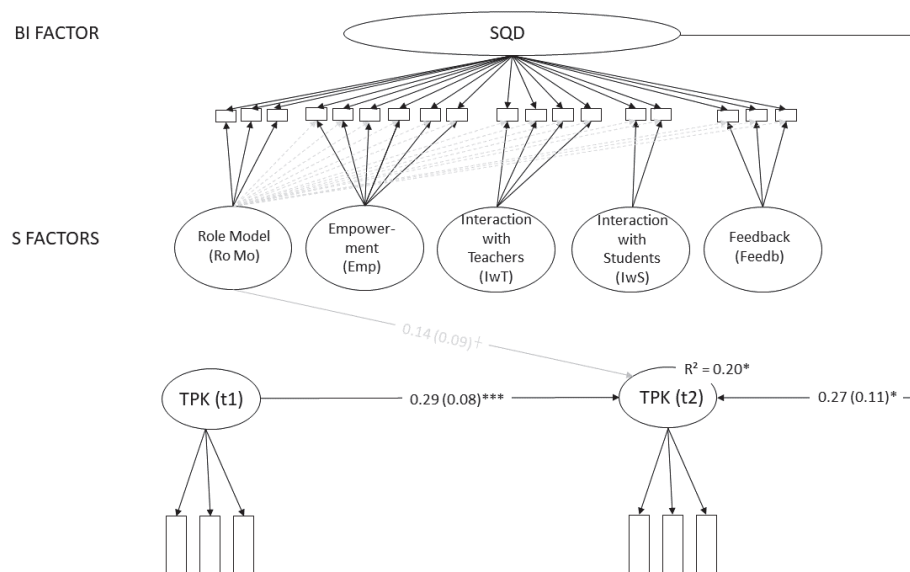


Figure 5. Model of the Exploratory Approach of SQD and TPK. *Note.* Grey arrow identifies marginal significant effects ($p \leq 0.10$).

Results on TPACK. The final results are presented in Figure 6. The model demonstrated good model fits: $\chi^2(217) = 339.596$, CFI = 0.972, TLI = 0.958, RMSEA = 0.043, SRMR = 0.034). First, the initial TPACK (t1) was positively related to the later perceived bi-factor of the SQD teaching strategies. Second, initial TPACK (t1) positively predicted later TPACK (t2). Third, self-perceived TPACK (t2) was positively predicated by the bi-factor of SQD while controlling for TPACK at the beginning of the semester (t1). The results indicated that the bi-factor, representing all examined teaching strategies, significantly and positively influenced the development of self-perceived TPACK (H2a). No meaningful effect was found for the S-factor with one exception of a marginal significant effect from the factor feedback on TPACK (t2) (H2b).

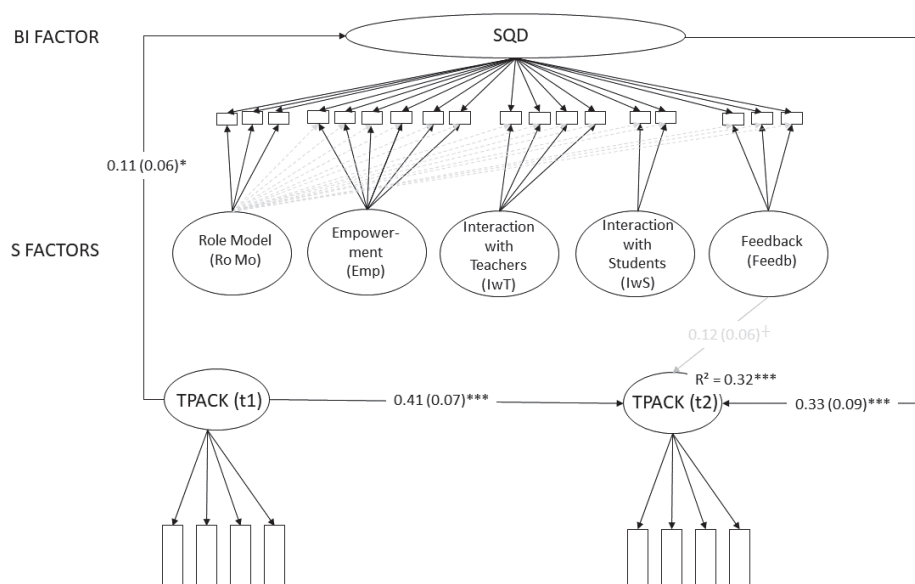


Figure 6. Model of the Exploratory Approach of SQD and TPACK. *Note.* Grey arrow identifies marginal significant effects ($p \leq 0.10$).

5. Discussion

This study aimed to investigate the development of self-perceived TPK and TPACK of pre-service teachers over time, with a focus on the influence of SQD teaching strategies on this development. Building on previous research, which has either focused on the orchestration [40,41] or individual strategies of the SQD model [37–39] and its impact on TPK and TPACK, we determined whether single strategies or the orchestration of all SQD teaching strategies enhance professional digital competence beliefs, i.e., TPK and TPACK. In the following, we want to discuss our four main findings, i.e., (1) the development of TPK and TPACK, (2) the development of TPK and (3) TPACK by considering the SQD teaching strategies, and (4) adjustments to the SQD model.

As a first result, our study found no general change in pre-service teachers TPK and TPACK across a semester without considering their learning experiences within seminars. These results are in line with Knezek and colleagues [40] and demonstrate that changes in TPK and TPACK might be dependent on learning experiences and thus teaching strategies employed within university classes. Furthermore, our results extend the findings of Johnson and colleagues [82], who found that TK does not change without support from instructors. All these results suggest, in general, that digital professional competence beliefs do not develop ‘naturally’; rather, students need particular learning experiences which flourish their professional development.

As a second main finding but contrary to our initial assumption (H1), our study results point to the fact that the orchestration of SQD teaching strategies positively influences the development of self-perceived TPK of pre-service teachers (RQ1). What this means is that pre-service teachers feel more competent in teaching with ICT after they participated in seminars that used all, i.e., the orchestration of, suggested teaching strategies from the SQD model. Interestingly, our results differ from previous research [48]. Lachner and colleagues [48] found no development of TPK in seminars designed according to the SQD model. However, they did not examine SQD teaching strategies as predictors but mentioned that learning experiences were designed according to the model. These differences in the research design might explain the discrepant results. Another potential explanation for the differing results compared to Lachner and colleagues [48] may lie in the nature of competency development as a long-term process. While they chose three sessions over three weeks for the study design, we took students’ learning experiences across 13 to 15 weeks within the semester into account. These differences in the time span may suggest that competencies require multiple and varied learning experiences over an extended period of time to develop. Furthermore, our focus extended beyond merely observing whether teaching strategies were observed; guided by the person–environment fit approach [59,60], we examined the satisfaction levels of the pre-service teachers with the teaching process, which could be a critical factor.

As a third main finding, we explored how pre-service teachers’ self-perceived TPACK develops in relation to the SQD teaching strategies (RQ2). Our study extended previous cross-sectional findings [43,44] by confirming a positive development of TPACK with higher satisfaction of pre-service teachers in strategies of the SQD model in an orchestrated manner (H2a). Contrary to previous research [38,45], which identified the significance of single strategies, i.e., authentic experiences, role models, and collaboration, for pre-service teachers’ TPACK development, we did not find single effects of these particular strategies. As a consequence, we had to reject our initial hypothesis (H2b), which was based on cross-sectional results [40,46,47]. We, however, need to note that our factor structure differs from previous studies as the factors authentic experiences, instructional design, and collaboration were not retained from the original SQD model [10,52].

As a last main finding, our investigation built on the work of Tondeur and colleagues [41] and Gümüs and colleagues [53] by examining the structure of SQD strategies in relation to four distinct stakeholders: instructors, peers, students, and in-service teachers. From a methodology perspective, our study contributes to the understanding and adjustment of the SQD model. We indicated a five-factor structure (role models, empowerment,

interaction with teachers, interaction with students, feedback) by considering the importance of various stakeholders to provide pre-service teachers a learning environment to develop digital competencies. We incorporated this focus in response to the findings of Tondeur and colleagues [44], which indicate that practical experiences significantly influence the development of TPACK. We propose that these practical experiences foster interactions with diverse stakeholders, which is why we have chosen to highlight this perspective in our study. Our results thus highlight the importance of different stakeholders for pre-service teachers' development of self-perceived TPK and TPACK, suggesting that the focus may not solely be on teaching strategies themselves but also on individuals with whom pre-service teachers can interact. This conclusion aligns with research from developmental psychology, which posits that different stakeholders become relevant and serve various functions throughout the individual learning process [56,57]. Tinto [57] emphasized that both academic and social systems are crucial for a successful college experience and the key to their academic success and social integration. For teacher education, though, teachers and instructors can influence the individual learning process for pre-service teachers as role models and knowledge providers, and peers for social and emotional support [24,57]. By considering these broader relationships, our findings suggest the potential for adjusting the SQD model to account for the influence of these stakeholders. Therefore, teacher training programs with a focus on ICT integration now have a starting point not only for teaching strategies but also for enhancing collaborative interactions between the stakeholders in a university context.

5.1. Limitations and Future Steps in Teacher Education Research

Despite the findings, limitations must be pointed out offering directions for future research. The study used data only from one university in Germany, which may limit the generalizability of the findings to other institutions. Notably, the diversity of studies shows that the findings build upon each other and exhibit similar trends, even when conducted at different universities, indicating that the results are generalizable [48].

Furthermore, we only considered seminars and not lectures as significant learning environments in teacher education. Given the potential differences in the number of students, the degree of the design, and instructional quality of these two learning formats, future research should explore potential distinctions between these learning formats' impact on the development of pre-service teachers TPK and TPACK.

Additionally, we conducted a linear change from two measurement points, which might limit our understanding of TPK and TPACK development from the beginning to the end of the seminars. The question of how TPK and TPACK evolve over time might be more complex and should be focused on in future research due to more measurement points allowing for the provision of a deeper insight into the development of TPK and TPACK of pre-service teachers.

Another limitation lies in the scope of our analysis of the SQD strategies. While we found that the bi-factor model and the individual strategies of role modeling or feedback significantly influenced the development of TPK and TPACK, we did not examine the specific content or methods as surface structures [83,84] used in the seminars presenting these strategies. Thus, it would be interesting to explore how the impact of the SQD strategies and the development of TPK and TPACK differ in seminars without digitalization content from seminars with the specific focus of digitalization. It would be particularly valuable to explore whether these strategies need to be applied consistently throughout an entire seminar or if specific, cumulative interactions are sufficient for pre-service teachers to develop TPK and TPACK. Also, future research might extend our study by investigating the interplay of surface structures (content, methods) and deep structures (teaching strategies) for the development of TPK and TPACK of pre-service teachers. Future research should focus on those questions through classroom observations and expand the findings generated from surveys to get a deeper insight of effective learning environments to develop pre-service teachers' digital competence.

Additionally, this study highlighted the importance of different stakeholders in the learning process of pre-service teachers. Future research could focus on those findings, exploring how the relationships and interactions between different stakeholders in the learning environment contribute to the development of TPK and TPACK of pre-service teachers. This could be achieved through qualitative methods like interviews or focus groups to gain a more nuanced understanding of the social dynamics within learning processes in teacher education seminars.

5.2. Implications and Conclusions

In conclusion, the present study contributes to a better understanding of the SQD model and its impact on the development of pre-service teachers' self-perceived TPK and TPACK. It could be specified that no single strategy is paramount; rather, the orchestration of all five SQD strategies is important, with each playing a specific role in the overall learning process in the context of stakeholders. Therefore, instructors in teacher education might focus on the combination of all strategies during their teaching in university seminars in an integrative way. A collection of ideas on how to implement these key strategies in teacher education can be found in the supplemental materials, part three. These are initial ideas, as they are based on findings from one university. Given the importance of orchestrating SQD teaching strategies, it is essential that the presented ideas be linked together. An exemplary seminar design might proceed as follows: Pre-service teachers first acquire an understanding of the concept of digital competencies, followed by self-reflection and the assessment of their individual basic and professional digital competence beliefs (e.g., TPACK). Based on this, they discuss with peers different strategies to enhance their TPACK and how to train their ICT use in class (Empowerment). Next, pre-service teachers design a micro-learning session incorporating ICT, with feedback from the instructor on how to improve the session (Feedback). This session is delivered to interested teachers (Interaction with teachers) and peers. Thus, participating peers are in the role of students and the pre-service teacher in the role of the teacher (Interaction with students). The pre-service teacher receives feedback from these stakeholders as well as the instructor after these micro-learning sessions (Feedback). At the end of the seminar, another self-reflection on their digital competencies (e.g., TPACK) takes place, and pre-service teachers reflect on their development (Empowerment). Throughout all stages, the instructor serves as a role model in ICT usage, demonstrating best practices (role model). In conclusion, identifying the different stakeholders and their impact on teaching processes and fostering interaction between them is crucial for the aim of supporting pre-service teachers' development of TPK and TPACK.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/educsci14121342/s1>.

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Article

Exploring the Influence of Vicarious Experiences in Teaching with Digital Technology on Pre-Service Science Teachers' Digitalization-Related Affective-Motivational Dispositions

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Abstract: The integration of digital media in German classrooms remains limited, partly due to teachers' low motivation, self-efficacy, and negative attitudes toward these tools. This study investigates how vicarious experiences influence pre-service teachers' digital media self-efficacy and attitudes toward digital media and how these dispositions influence their motivational orientation toward using digital media in teaching. Beyond this, personal experiences were implemented via an ecologically valid intervention, and their influence on the respective constructs was examined. This study employed a longitudinal design involving 43 pre-service science teachers over an internship semester, combining a theoretical workshop at the university with lesson planning, implementation, and reflection. Data were collected pre- and post-intervention and analyzed using Bayesian Path Analysis to examine the relationships between the constructs. T-tests were applied to investigate the impact of structured mastery experiences. The results imply that vicarious experiences influence attitudes but have no significant influence on self-efficacy. Motivational orientation is primarily influenced by attitudes but not by self-efficacy and has a positive effect on the frequency of media use. Self-efficacy, on the other hand, was most strongly influenced by mastery experiences, whereas attitudes received the least support in this regard.

Keywords: teaching with digital media; motivational beliefs; attitudes and orientations on digital media in teaching; promoting digital media competences

1. Introduction

Teaching science is challenging since science content often requires students to comprehend complex systems involving a high level of abstraction (Goldstone & Sakamoto, 2003). Digital media show new ways of dealing with these challenges and thus have the potential to transform teaching and learning (Becker et al., 2020; Hillmayr et al., 2020). This can be attributed to the inherent characteristics of digital media, which enable a more flexible adaptation to students' prior knowledge and promote cognitive activation as well as explorative learning (Hillmayr et al., 2020). To achieve this transformation, science teachers must implement digital media in a targeted and meaningful way. However, the implementation of digital media remains limited in German classrooms (Eickelmann et al., 2019). Furthermore, science teachers use digital media primarily for administrative tasks and to augment traditional teaching methods rather than fundamentally enhancing instructional quality (DeCoito & Richardson, 2018; Kramer et al., 2019; Pringle et al., 2015; Szeto &

Cheng, 2017). To optimize the use of digital media in class, teachers need digitalization-related professional knowledge. Alongside professional knowledge, affective-motivational factors represent central elements of professional teaching behavior (Baumert & Kunter, 2013; Weinert, 2001). This also applies to implementing digital media in the classroom (Backfisch et al., 2021; Pozas et al., 2022; Vogelsang et al., 2023). Affective-motivational dispositions toward digital media are even considered more critical for the (effective) use of digital media than external factors such as school characteristics or available infrastructure (Drossel et al., 2017; Lee & Lee, 2014). In other words, promoting motivational orientation to use digital media in class—defined as teachers’ general inclination or drive to incorporate digital media into their (future) practices—has become a central challenge in teacher education (McGarr & McDonagh, 2020; Schleicher, 2020; Vogelsang et al., 2019). Studies indicate that (pre-service) teachers’ motivational orientations toward the use of digital media in teaching are influenced by corresponding attitudes and self-efficacy (Kindermann & Pohlmann-Rother, 2022; Kreijns et al., 2013; Vogelsang et al., 2019, 2023). Additionally, teachers’ attitudes and self-efficacy beliefs toward digital media have been shown to significantly impact the frequency of technology use in teaching (Drossel et al., 2017) as well as students’ learning achievements in digitally enhanced teaching situations (Cheng & Weng, 2017; Eldaou, 2016). Consequently, the comparatively low frequency and poor quality of digital media integration in German classrooms may be partially attributed to teachers’ comparatively low affective-motivational dispositions toward using digital media in teaching. In turn, both teachers’ attitudes and self-efficacy toward the use of digital media have been shown to be affected by personal and vicarious experiences (Kreijns et al., 2013). Ultimately, one way to foster pre-service teachers’ motivational orientations toward using digital media is through personal as well as vicarious experiences, such as observations during school placements. To date, there has been little research on the role of vicarious experiences in developing pre-service science teachers’ motivational orientations toward digital media. Moreover, research is rare on how self-efficacy and attitudes interact regarding the development of pre-service teachers’ motivational orientations and to what extent these actually influence pre-service teachers’ behavioral measures. Our study aims to add to the body of research on these aspects (see Research Objectives and Hypotheses). To this end, we will first discuss the constructs of technology-related self-efficacy and attitudes toward digital media in teaching and review the state of research on ways to promote these constructs.

1.1. Technology-Related Self-Efficacy as an Aspect of Teachers’ Profession

According to Bandura’s Social Cognitive Theory of Learning, self-efficacy represents a key factor affecting individuals’ motivation and persistence in challenging tasks (Bandura, 1977, 1997). Self-efficacy is an individual’s belief in their ability to execute actions necessary to produce desired outcomes successfully. Higher self-efficacy leads to more effort and perseverance, while lower self-efficacy results in avoidance behavior and reduced motivation (Caprara et al., 2006; Klassen et al., 2009). Accordingly, pre-service teachers with high self-efficacy toward digital media are more likely to engage with digital tools (Li et al., 2019), try innovative methods (Joo et al., 2018), use technology more effectively for teaching purposes (Hoy et al., 2009), and persist despite external challenges (Heath, 2017; Li et al., 2019). In line with this, teachers’ self-efficacy is furthermore associated with instructional quality (Holzberger et al., 2013; Klassen & Tze, 2014), students’ learning processes, and learning outcomes (Klassen & Tze, 2014). Thus, it can be considered an aspect of teachers’ profession. Self-efficacy is considered highly domain-specific and depends on the context of its application (Straub, 2009), including the individual digital media used (Holden & Rada, 2011).

Consequently, numerous instruments have been developed to measure self-efficacy in using digital media, such as Computer Self-Efficacy (Murphy et al., 1989), Internet Self-Efficacy (Hsu & Chiu, 2004), and digital -media self-efficacy (Pumptow, 2020). However, Zeng et al. (2022) found no significant moderating effect of different instruments on the relationship between self-efficacy in teaching with digital media and constructs like the Technological Pedagogical And Content Knowledge (TPACK), leading to the assumption that they measure very similar latent constructs. Kiili et al. (2016) also demonstrated that teachers' self-efficacy in using digital media strongly correlates with self-efficacy in integrating digital media in teaching and accordingly emphasizes the relevance of promoting all levels of teachers' technology-related self-efficacy.

1.2. Positive Attitudes Toward Digital Media as an Aspect of Teachers' Profession

The Theory of Planned Behavior (Ajzen, 1991) posits that humans' behavioral intention is jointly influenced by three kinds of factors, which in turn predict actual behavior: (i) attitudes toward the behavior, (ii) subjective norms, and (iii) perceived behavioral control. Attitudes reflect the favorable or unfavorable evaluation of a behavior, indicating how positively or negatively individual judges or appraises that behavior (Ajzen, 1991). In line with the Theory of Planned Behavior, some studies identified positive attitudes as the strongest predictor of teachers' intentions (Anderson et al., 2011; Teo et al., 2016) or motivational orientation (Vogelsang et al., 2019) to use digital media and the frequency of technology usage in teaching (Anderson et al., 2011). In this context, attitudes—encompassing teachers' beliefs about the benefits of integrating digital media in teaching for students' learning and preparation for professional life—occasionally outperformed self-efficacy as a predictor of intentions (Anderson et al., 2011; Vogelsang et al., 2019). The impact of subjective norms has been relatively low on the other side (Kreijns et al., 2013; Vogelsang et al., 2019). Finally, perceived behavioral control, closely related to Bandura's concept of self-efficacy (Ajzen, 1991), is also proven to impact pre- and in-service teachers' motivational orientation toward using digital media (Vogelsang et al., 2019) and the effective use of technology in teaching (Pozas et al., 2022).

However, German pre-service teachers often report cautious or negative attitudes toward using digital media for teaching, often due to fears of being overwhelmed, doubts about the competences to be promoted, and concerns about health risks associated with digital media (Braun et al., 2022). These attitudes are unfavorable concerning a change in the use of digital media. Moreover, teacher beliefs are noted for their high stability as individuals actively seek confirmation of their existing belief system and reject contradictory information (Gregoire, 2003). The stability of teachers' belief system accordingly increases with ongoing professional experiences as beliefs become less accessible to teachers' awareness the more they integrate into everyday interpretation patterns (Reusser & Pauli, 2014). Conversely, it could be assumed that dispositions such as motivational attitudes and self-efficacy are not as firmly established in pre-service teachers and are more malleable than those of in-service teachers (De La Torre Cruz & Casanova Arias, 2007)—one reason to promote positive attitudes toward using digital media for teaching in pre-service teacher education.

So far, this appears not to be considered in German teacher education. German in-service teachers state that they acquired technology-related teaching skills rather incidentally than through systematic instruction (Eickelmann et al., 2022). Yet, only a small proportion participate in technology-related professional development courses (Gerick et al., 2019), which could be attributed to inadequate training programs (Diepolder et al., 2021). This underscores the need for targeted as well as structured interventions in early

teacher education to disseminate knowledge and foster positive attitudes toward digital media in teaching and digital media self-efficacy.

1.3. Fostering Pre-Service Teachers' Digital Media Self-Efficacy and Positive Attitudes Toward Digital Media

Bandura (1997) identifies four primary sources of self-efficacy: (i) personal mastery experiences, (ii) vicarious mastery experiences, (iii) verbal persuasion, and (iv) physiological or emotional states. Personal mastery experiences involve successful task completion, reinforcing one's capability beliefs. Vicarious mastery experiences occur through observing others' successes, influencing self-efficacy based on perceived similarity. Verbal persuasion includes encouragement from others, potentially bolstering confidence when credibility is perceived. Lastly, physiological and emotional states, such as anxiety or stress, affect self-efficacy perceptions.

Consequently, it can be assumed that integrating personal and vicarious mastery experiences with digital media in teaching, for example during internship semesters, may have the power to foster pre-service teachers' digital media self-efficacy (Pozas et al., 2022; Tondeur et al., 2012). Numerous empirical studies have reported the influence of personal (mastery) hands-on teaching experiences on digital media or technology-related self-efficacy (Al-Awidi & Alghazo, 2012; Anderson et al., 2011; Aumann & Weitzel, 2023; Bautista, 2011; Han et al., 2017; Paetsch et al., 2023; Kiili et al., 2016; Li et al., 2019; Pfitzner-Eden, 2016; Vogelsang et al., 2023). For example, Vogelsang et al. (2023) addressed the development of pre-service science teachers' attitudes, self-efficacy and motivational orientations toward digital media. In this study, the use of digital media in remote teaching during the second COVID-19 lockdown had a slightly negative effect on the pre-service science teachers' attitudes toward digital media, while their self-efficacy and motivational orientations toward digital media increased.

Though there is evidence on the importance of vicarious experiences in using digital media in teaching on teachers' affective-motivational dispositions (Wang et al., 2004), little is known about the relevance of vicarious experiences compared to personal experiences. Nevertheless, especially in the early stages of teacher education, observing role models seems to be of great importance (Pfitzner-Eden, 2016). Moreover, research rarely moves beyond the motivational level to examine the effects of technology-related self-efficacy on actual behavioral measures, such as the use of digital technologies in teaching (Wang et al., 2004).

With a focus on positive attitudes toward the use of digital media in the classroom, previous research has shown that these have to be assumed as more stable dispositions (Valtonen et al., 2021; Vogelsang et al., 2019, 2023). For example, while lesson planning positively impacted technology-related self-efficacy, no significant changes were found in technology-related attitudes (Lee & Lee, 2014). Lee and Lee (2014) suggest that lesson planning alone is insufficient to change the motivational attitudes of pre-service teachers and recommend carrying out activities that comprehensively represent real classroom practice. There is also evidence that experiences need to be sufficiently subject-specific to be transformed into attitudes (Blömeke, 2007). As attitudes toward digital media are seen as a result of reflecting on past experiences (Ajzen, 1991), vicarious experiences through observing role models successfully using digital media in teaching are also considered an influencing factor (Anderson et al., 2011). The results of a study conducted by Meagher et al. (2011) suggest that pre-service teachers who completed their internship in technology-rich school environments developed more positive attitudes toward the use of technology in the classroom than those who completed their internship in schools with minimal use of technology. This is also supported by research, indicating that observed media-related

teaching from one's own school years influence pre-service teachers' technology-related attitudes (Blömeke, 2007).

1.4. Research Objectives and Hypotheses

The aim of the study is to contribute to the understanding on how motivational beliefs, attitudes, and orientations toward using digital media in teaching can be fostered. So, this study focused on changes in using digital media in teaching and related (motivational) beliefs, attitudes, and orientations of pre-service science teachers (instead of their characterization). In detail, based on the assumptions of the Theory of Planned Behavior (Ajzen, 1991), we assume that the use of digital media increases when pre-service science teachers' motivational orientation grows, which in turn is based on increased digital media self-efficacy and increased positive attitudes toward digital media. Furthermore, based on the Social Cognitive Theory of Learning (Bandura, 1977), we assume that both digital media self-efficacy and positive attitudes toward digital media are fostered by vicarious experiences (observed behavior) in using digital media. Specifically, the study aims to investigate the following three hypotheses:

H1. *Pre-service science teachers' use of digital media in teaching increases when their motivational orientation toward using digital media in teaching grows.*

H2a. *Pre-service science teachers' motivational orientation in using digital media in teaching grows when their digital media self-efficacy increases.*

H2b. *Pre-service science teachers' motivational orientation in using digital media in teaching grows when their positive attitudes toward digital media in teaching increase.*

H3a. *Pre-service science teachers' digital media self-efficacy increases when there are increasing vicarious experiences (observed behavior) in using digital media in teaching.*

H3b. *Pre-service science teachers' motivational orientation in using digital media in teaching increases when there are increasing vicarious experiences (observed behavior) in using digital media in teaching.*

2. Materials and Methods

2.1. Study Design and Sample

The present study involved a longitudinal design to assess changes in the constructs of interest due to a specific intervention and practical experiences during the school internship. In this regard, all pre-service biology teachers at the university were accompanied during their internship semester over 3 consecutive semesters. This involved 61 pre-service science teachers in their master's studies. Complete pre–post datasets ($n = 43$) were collected over the course of the study. In summary, the intervention consisted of a preparatory workshop offered at the beginning of the internship semester in the accompanying seminar and the subsequent implementation of a technology-supported lesson in class. The preparatory workshop and the following implementation focused on a specific use of digital media in science teaching (student-generated explainer videos). The intervention's development (see, Aumann & Weitzel, 2022) included empirical evidence regarding student-generated explainer videos in science teaching and considered the criteria of Tondeur et al. (2012) while building on the Transformation Model of Lesson Planning (Stender et al., 2017). In the preparatory workshop (180 min.), the pre-service science teachers (1) acquired theoretical knowledge on the use of digital media in science teaching via online materials, (2) developed lesson plans and discussed exemplary lesson plans in peer collaboration,

and (3) gained experience in creating explainer videos themselves to learn about different video production methods. Following the preparatory workshop, the students moved on to their school internship of 14 weeks. As part of the internship, they (4) planned a lesson in which explainer videos were used to contribute to a deeper understanding of the science content. The lesson was then (5) carried out and (6) reflected on with the support of the first author. Participants were surveyed via pre–post tests using validated scales to measure the constructs of interest (see Instruments, Section 2.2). Pre tests were collected after the workshop at the university, while the post tests were collected approximately one week after the pre-service teachers’ lesson reflection. Using this approach, the intervention was firmly grounded in empirical research and ecologically valid in its implementation in the context of an internship semester in Germany. In addition to attending their own scheduled classes, the pre-service teachers were allowed to observe and learn from experienced teachers in several other lessons. These in-service teachers at the internship schools served as role models, providing the pre-service teachers with the chance to gain vicarious experiences through observation.

2.2. Instruments

Validated survey instruments were used to assess the latent constructs. The majority of the scales were already available and validated in German language. Only the scale measuring vicarious experiences had to be translated into German. All scales showed good internal consistencies (see Table 1). The constructs were standardized using items on a 6-point Likert scale from “1 = I don’t agree at all” to “6 = I completely agree”. An exception to this was the single item scale for surveying the frequency of use of digital media in teaching. All scales are therefore based on the participants’ self-reports. Accordingly, the quality of the role models in this study is not based on a normative measure but on the subjective assessments of the participants themselves.

Table 1. Scales used and their validity.

Construct	Exemplary Item	Reference	Validity	Items
Vicarious experiences using digital media in teaching (VEDM)	<i>“I saw good examples of ICT practice that inspired me to use ICT applications in the classroom myself.”</i>	Tondeur et al. (2016)	Cronbachs’ $\alpha = 0.875$ (Pre) $\alpha = 0.928$ (Post)	4
Digital media self-efficacy (DMSE)	<i>“I am relaxed about difficulties when dealing with digital media, because I can always trust by abilities.”</i>	Pumptow (2020)	Cronbachs’ $\alpha = 0.957$ (Pre) $\alpha = 0.946$ (Post)	7
Positive attitudes toward digital media in teaching (PADM)	<i>“The use of digital media enables a high degree of self-determined learning.”</i>	Vogelsang et al. (2019)	Cronbachs’ $\alpha = 0.822$ (Pre) $\alpha = 0.881$ (Post)	8
Motivational orientation toward digital media in teaching (MODM)	<i>“I am very interested in thinking about how I can better support my students’ learning with the help of digital media.”</i>	Vogelsang et al. (2019)	Cronbachs’ $\alpha = 0.865$ (Pre) $\alpha = 0.916$ (Post)	6
Frequency of use of digital media in teaching (FUDM)	<i>“How often have you systematically used digital media to achieve specific learning objectives in your own teaching and learning programs (e.g., internships, seminars)?”</i>	Single-item scale with 5 response categories ranging from 0 to over 15 times.		

Table 1 provides an overview of the scales used and their internal consistencies among the samples. In addition, the frequency of use of digital media in the classroom was surveyed. In Appendix A, all items of the different scales are presented.

2.3. Data Analysis

At first, to test for the interventions' impact regarding the pre-service science teachers' affective-motivational dispositions, changes in central tendencies of the constructs were assessed using paired *t*-tests to compare pre- and post-intervention scores.

To test the hypothesized relationships among the variables, Bayesian Path Analysis was conducted using R (version 4.4.1) and the blavaan software package (version 0.5.6). Bayesian methods offer particular advantages for small sample sizes by enabling the inclusion of prior knowledge in the estimations (König & Van De Schoot, 2018). The capabilities of this methodological framework have increasingly led to its application in data analysis within educational research (Kaplan & Harra, 2024). In particular, using weakly informative or informative priors is recommended in the context of small sample sizes (Smid & Rosseel, 2020), as this allows for better model fits (Muthén & Asparouhov, 2012).

2.3.1. Data Preparation and Model Specification

Initially, based on the underlying theories, relationships between the variables were hypothesized and the data was checked for outliers, normal distribution, and multicollinearity using SPSS (version 29.0.2.0). This was essential to ensure the validity and reliability of the subsequent Bayesian Path Analysis.

Model Specification

The model specification is based on Hypotheses 1 to 3 (see Figure 1). The changes in each variable were considered by controlling its expression on measurement point 2 by its expression on measurement point 1.

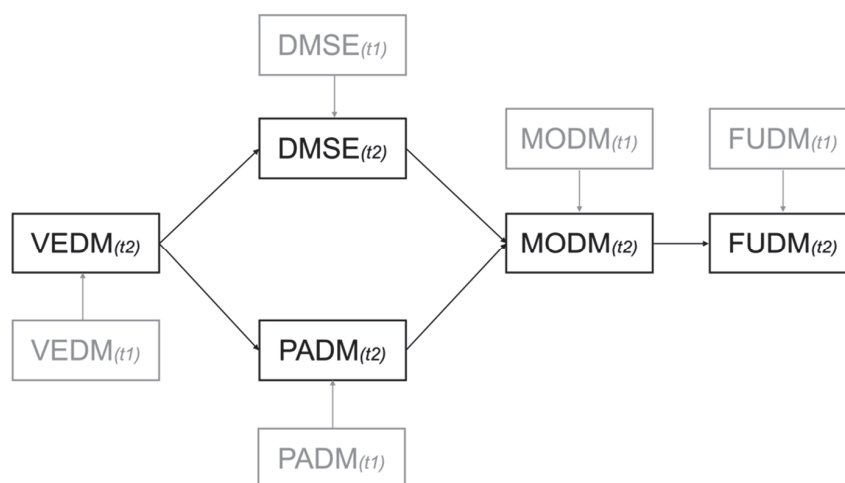


Figure 1. Hypothesized path model. Autoregressive pathways and constructs at t1 are grayed out.

The hypothesized model specifications were then estimated using Bayesian Path Analysis. Variances for independent variables (e.g., PADM(t1)) were not included in the model to reduce the number of parameters, keep the model identifiable, and minimize complexity. These variables are treated as independent input factors.

Outliers

Each variable was Z-standardized to identify outliers, and the resulting Z-scores were compared against the established cutoff value of ± 3 . Data points with Z-scores exceeding

this threshold were interpreted as outliers. No outliers were identified in the dataset that exceeded the cutoff value of ± 3 for the Z-scores.

Normal Distribution

A Shapiro–Wilk test was employed to assess normality, as it is more reliable for smaller sample sizes due to its higher power in detecting deviations from normality compared to the Kolmogorov–Smirnov test (Razali & Wah, 2011). To further ensure the adequacy of the normality assumption, skewness and kurtosis values were examined for variables where the Shapiro–Wilk test indicated potential non-normality. The cutoff values proposed by West et al. (1995) were applied, where skewness values exceeding 2 and kurtosis values exceeding 7 were considered significant deviations from normality. These additional criteria helped identify any violations that could impact the accuracy and reliability of the statistical analyses.

Although the Shapiro–Wilk test indicated non-normality for DMSE(t2), FUDM(t1), and FUDM(t2) (with significant *p*-values), neither the skewness nor the kurtosis values exceeded the established cutoff thresholds (highest skewness: 0.710, highest kurtosis: -1.478). As a result, these slight deviations from normality were not considered problematic for the subsequent analyses.

Multicollinearity

Correlation matrices were generated to examine the Pearson correlations between (1) VEDM(t2) & DMSE(t1), (2) VEDM(t2) & PADM(t1), (3) PADM(t2), DMSE(t2) & MODM(t1), and (4) MODM(t2) & FUDM(t1). Established thresholds were applied, with correlations exceeding 0.7 indicating potential multicollinearity.

No multicollinearity was detected in the Pearson correlation matrix, with the highest observed correlation being 0.520. This value is well below the commonly accepted threshold for multicollinearity of 0.7.

2.3.2. Bayesian Path Analysis

Bayesian Path Analysis was performed following the “When to worry and how to avoid the misuse of Bayesian statistics” (WAMBS) checklist by Depaoli and Van De Schoot (2017). Estimations were conducted using the R software with the Stan package (version 2.32.6), which implements the Hamiltonian Monte Carlo (HMC) algorithm within the Markov Chain Monte Carlo (MCMC) framework. Detailed information on the prior specification, convergence, autocorrelation, posterior distribution, sensitivity analysis, and evaluating model fit are presented in Appendix B.

3. Results

3.1. Descriptives and Results of the *t*-Test

Table 2 provides an overview of the data by displaying the means and standard deviations of the individual constructs at time points t1 and t2.

Table 2. Descriptive statistics of the constructs surveyed in study 2 at t1 and t2 (measured on a Likert Scale from 0 to 6).

	MODM (t1)	MODM (t2)	PADM (t1)	PADM (t2)	DMSE (t1)	DMSE (t2)	VEDM (t1)	VEDM (t2)	FUDM (t1)	FUDM (t2)
Arithmetic Mean Value	3.760	4.205	4.407	4.762	3.700	4.269	3.366	3.465	2.910	3.370
Standard Deviation	1.075	1.111	.877	.781	1.327	1.181	1.178	1.421	1.130	1.176

Table 3 presents the results of the mean comparison between the constructs pre- and post-intervention. Paired *t*-tests indicate significant increases with high effect sizes across all constructs. The highest effect sizes are observed in pre-service science teachers' digital media self-efficacy (Cohen's *d* = 1.13), while attitudes exhibit the relatively lowest change in mean values (Cohen's *d* = 0.816).

Table 3. Paired *t*-test results comparing t1 and t2.

	MODM	PADM	DMSE
Significance (Two-Sided)	$p < 0.001$	$p = 0.003$	$p < 0.001$
Cohen's <i>d</i>	0.899	0.816	1.13

3.2. Results of the Hypotheses

The estimated model demonstrated a strong fit to the data, as indicated by the Posterior Predictive *p*-Value (ppp) of 0.539. Additionally, the Bayesian Root Mean Square Error of Approximation (BRMSEA) was 0.001, well below the threshold of 0.05, indicating an excellent fit. However, as already noted, this value must be interpreted with caution in consideration of the small sample size. Nevertheless, the fit indices collectively suggest that the model accurately represents the underlying structure of the data. Figure 2 depicts a visual representation of the path model, including the estimated regression paths, to further illustrate the relationships between the variables. Autoregressive paths across all variables show a similar pattern, indicating moderate temporal stability within constructs.

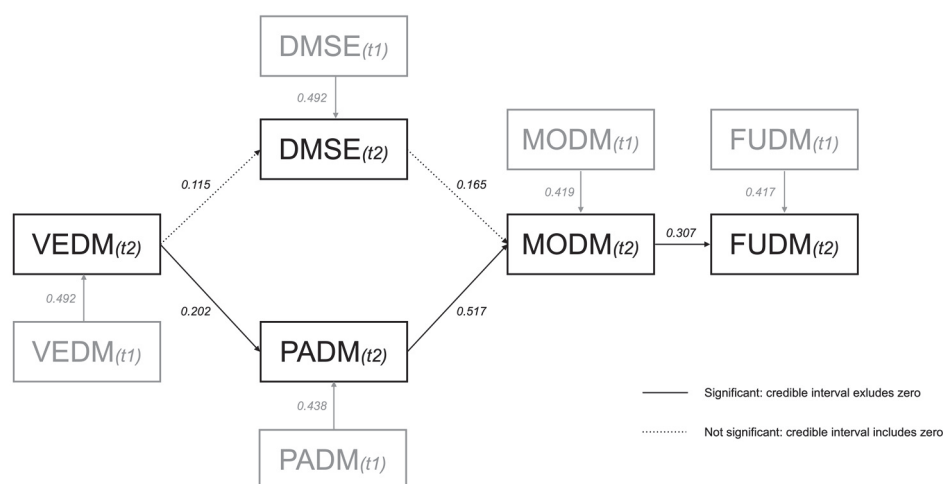


Figure 2. Bayesian path model depicting the posterior regression estimates. Autoregressive pathways and constructs at t1 are grayed out.

With regard to the hypotheses, the results indicate that pre-service science teachers' use of digital media in teaching increases when their motivational orientation in using digital media grows (H1). Further, the results gave evidence that pre-service science teachers' motivational orientation in using digital media in teaching grows when their positive attitudes toward digital media increase (H2b). There was no effect of pre-service science teachers' increased self-efficacy on their increased motivational orientation in using digital media in teaching (H2a). Finally, increasing vicarious experiences (observed behavior) in using digital media resulted in positive changes in pre-service science teachers' positive attitudes toward digital media (H3b) but not their digital media self-efficacy (H3a).

4. Discussion

Digital technology and media are rarely used to enhance student learning in science education in Germany. Based on Bandura's Social Cognitive Theory and the Theory of Planned Behavior, we aimed to understand how vicarious experiences with digital media shape teachers' affective-motivational dispositions, which are vital for integrating digital technology in class. We employed a longitudinal design to investigate how vicarious experiences influence pre-service science teachers' attitudes toward digital media and their digital media self-efficacy. Additionally, we investigated the impact of these attitudes and self-efficacy beliefs on the pre-service science teachers' motivational orientation to use digital media and the frequency of usage in their teaching. According to the theoretical frameworks, hypothetical relationships were specified and examined using Bayesian Path Analysis. We examined these relationships over an internship semester including a targeted intervention. The results indicated that vicarious experiences positively influence pre-service science teachers' attitudes toward digital media in teaching, which, in turn, enhance their motivational orientation toward implementing digital media. This heightened motivational orientation ultimately results in a more frequent use of digital media in the classroom. On the other hand, the results showed that vicarious experiences did not appear to impact pre-service science teachers' digital media self-efficacy, which in turn does not significantly influence their motivational orientation toward digital media in teaching.

The findings support the argument that rare use of digital media in teaching can be partially attributed to teachers' low motivation or negative attitudes toward using these tools (Cheng & Weng, 2017; Drossel et al., 2017; Eldaou, 2016; Lee & Lee, 2014) and highlight—once again—the importance of fostering motivational beliefs, attitudes, and orientations in the use of digital media in teacher education (Baumert & Kunter, 2013; Stender et al., 2017; Weinert, 2001). Additionally, the study design indicates that this can be achieved through a preparatory workshop offered at the beginning of an internship semester in the accompanying seminar and the subsequent realization of a technology-supported lesson in the classroom. In this context, self-efficacy, on which the intervention had the strongest effect, should be emphasized, implying that evidence-based structured interventions in using digital media in teaching can promote successful mastery experiences for fostering pre-service science teachers' technology-related self-efficacy (Kiili et al., 2016; Paetsch et al., 2023). Moreover, the findings highlight the relevance of role models in using digital media in teaching to foster students' professional motivational beliefs, attitudes, and orientations. These role models can be university teachers or internship supervisors, for example. Empirical work indicates that university teachers and internship supervisors are not well experienced per se in using digital media in teaching (DeCoito & Richardson, 2018; Kramer et al., 2019; Pringle et al., 2015; Szeto & Cheng, 2017), so complementary teacher training is necessary to support the development of digital media competences.

The missing link between vicarious experiences and students' self-efficacy beliefs could be explained as follows: Social Cognitive Theory highlights mastery experiences as the most potent source for developing self-efficacy (Bandura, 1977, 1997), which also applies to the digital media-related self-efficacy of pre-service teachers (Bautista, 2011; Pfitzner-Eden, 2016). In the present study, this is evident from the notably strong impact of the intervention on the pre-service science teachers' digital media self-efficacy (Cohen's $d = 1.13$), which exhibited the most remarkable growth among all of the constructs. Accordingly, the missing relationship between vicarious experiences and digital media self-efficacy might be attributed to the particularly strong influence of mastery experiences during the intervention, potentially overshadowing the impact of vicarious experiences. Additionally, according to Social Cognitive Theory, vicarious experiences are most effective when individuals can identify with the role models they observe. For pre-service teachers who have

no choice regarding the accompanying teachers at their internship school and with limited practical experience, establishing such identification with the role models may be challenging. While pre-service teachers may develop positive attitudes by observing teaching with digital media, these vicarious experiences might not translate into enhanced self-efficacy. A potential misalignment between the self-perception of pre-service teachers and their role models due to a perceived gap between their abilities and those of the in-service teachers could prevent pre-service science teachers from applying these observed experiences to strengthen their self-efficacy in using digital media. Furthermore, although Bandura's theory (Bandura, 1977, 1997) highlights the significance of self-efficacy, it can be argued that in the early stages of teacher training and within initial practical encounters, attitudes shaped by vicarious experiences exert a more substantial influence. During early phases, such as the internship semester, fundamental attitudes toward the teaching profession are formed. These initial attitudes may impact motivational orientation more than developing self-efficacy beliefs, as pre-service teachers have few personal success experiences and rely heavily on their mentoring teachers at the respective internship schools. Self-efficacy may gain importance for motivational orientation with increasing successful personal and self-directed experiences.

A key limitation of this study is the small sample size of $n = 43$, which challenges the generalizability and robustness of the findings. The small sample is due to three reasons: (1) The number of pre-service teachers at our university was limited. The sample already corresponded to a complete survey of the respective cohort. (2) Pre-service teachers from other universities could not be included in the study due to the intensive and individualized intervention, which required close collaboration and accompaniment between the first author and each school. (3) The intervention involved an elaborate lesson planning, implementation, and reflection process, with personalized guidance for each participant over three consecutive semesters.

While Bayesian methods were employed to mitigate the small sample by incorporating prior knowledge, caution in interpreting the results is still necessitated, as there is a risk of overfitting to the study's specific context. The priors used in the Bayesian analysis notably influenced the posterior estimates (see the results of the sensitivity analysis in Appendix B). This further highlights the need for larger samples in future research to ensure more robust and generalizable outcomes. Additionally, incorporating informative priors resulted in only slightly reduced model complexity, as indicated by the effective number of parameters (see Appendix C). Moreover, the study was conducted under specific contextual conditions: pre-service teachers from a university in southern Germany using a specific technology (student-generated explainer videos) in science teaching. This contextual specificity limits the external validity of the findings and suggests that the results may not be fully applicable to other teaching contexts, subject areas, or geographical regions. As such, this study represents a first approximation to the research question. To ensure the reliability and representativity of the findings, further research is needed with larger sample sizes and in diverse educational settings. Such studies will help to validate the current results and extend their applicability to broader contexts.

Due to the small sample, no control group could be added to carry out an experimental approach. Correspondingly, the findings on the intervention's influence on the constructs should also be interpreted with caution, as there are numerous different influences on the pre-service teachers during the internship semester.

Based on the findings, several practical recommendations can be made for teacher education programs, although these should always be understood in light of the aforementioned limitations. First, we propose a methodological differentiation in teacher education—taking into account the training level of pre-service teachers—when it comes to fostering

affective-motivational dispositions toward the use of digital media in the classroom. Early teacher education should initially incorporate opportunities to observe others successfully using digital media. This could be achieved, for example, through video demonstrations, peer observations, or mentorship programs. This way, the pre-service teachers' attitudes toward digital media can be fostered, motivating them to use technology in their future teaching. In this respect, subsequent teacher education programs should also aim to create a wide range of opportunities to use digital media in the classroom, which can be implemented through internships. Additionally, providing pre-service teachers with structured opportunities to plan, implement, and reflect on the use of digital media in authentic classroom settings seems crucial to enabling positive experiences. Workshops, internships, and practicum experiences should include targeted interventions focusing on technology integration and combining theoretical inputs with practical experiences. These mastery experiences should contribute to the development of pre-service teachers' self-efficacy.

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Appendix A

Items for each of the scales.

Construct	Items	Reference
Vicarious experiences using digital media in teaching (VEDM)	During my studies or internship...	Tondeur et al. (2016)
	• I saw good examples of ICT practice that inspired me to use ICT applications in the classroom myself	
	• I saw many examples of ICT use in an educational setting	
	• I observed sufficient ICT use in an educational setting in order to integrate applications myself in the future	
	• The potential of ICT use in education was demonstrated concretely	

Construct	Items	Reference
Digital media self-efficacy (DMSE)	• I am relaxed about difficulties when dealing with digital media, because I can always trust by abilities. • If something doesn't work with the use of digital media, I find ways and means to make it work. • I have no difficulty in realising my intentions and goals in connection with a media application. • Whatever happens when dealing with digital media, I can handle it. • For every problem in connection with digital media I can find a solution. • When I am dealing with a new media application, I know to handle it. • If a problem arises concerning a media application, I can handle it by my own.	Pumptow (2020)
Positive attitudes toward digital media in teaching (PADM)	• The use of digital media enables a high degree of self-determined learning. • Digital media should generally be given a strong emphasis in school curricula. • Pupils can be better motivated to learn through the use of digital media. • Computers and digital media open up scope for creativity in learning. • The use of digital media at school ensures that children are well prepared for working life. • Learning with digital media is an efficient form of learning. • With digital media, I can plan and adapt lessons to suit the target group. • Digital media allow greater student activation.	Vogelsang et al. (2019)
Motivational orientation toward digital media in teaching (MODM)	• I am very interested in thinking about how I can better support my students' learning with the help of digital media. • I enjoy thinking about how I can use digital media in the classroom. • I also find out in my free time what possibilities there are for integrating digital media in lessons. • I like to familiarise myself with the operation of digital media (e.g., programmes) for lessons. • I am prepared to invest a little more time in lesson preparation if I can use digital media in my lessons. • Selecting or creating digital media for lessons is one of the most interesting parts of lesson preparation. • Digital media allow greater student activation.	Vogelsang et al. (2019)

Appendix B

Information on the prior specification, convergence, autocorrelation, posterior distribution, sensitivity analysis, and evaluating model fit:

(i) Prior Specification

The path model estimated regression and variance parameters using informative priors. Prior specification can have a strong impact on parameter estimation, especially in small sample studies. Therefore, it is essential to define and interpret priors with caution and to report them transparently.

Two techniques were used to define the hyperparameters of the informative priors. First, we drew on an empirical study by Vogelsang et al. (2023) conducted under comparable contextual conditions. Second, expert estimates were incorporated. Specific regression coefficients were drawn from the results of Vogelsang et al. (2023), providing a robust basis for prior predictions due to the similarity of the study. The referenced research examined a mediation analysis that included self-efficacy, attitudes, and motivational orientation toward teaching with digital media among pre-service science teachers during their internship semester. In addition, the same scales for attitudes (PADM) and motivational orientations (MODM) were used in Vogelsang et al. (2023). These regression coefficients, adopted from the source, were rounded to one decimal place as priors to provide initial information and ensure robust estimates.

The default standard deviation of the priors was set to 0.1 in order to keep the priors fairly informative. Nevertheless, the following uncertainties were considered in estimating the prior standard deviations. First, the regression coefficients in Vogelsang et al. (2023) were based on a 7-point Likert scale, while this study used a 6-point Likert scale. Therefore, a standard deviation of 0.2 was defined for all prior regression parameters to reflect this difference in scale.

Second, Vogelsang et al. (2023) differentiated three facets of self-efficacy for technology use in the classroom that were regressed on attitudes and motivational orientation in three separate path analyses. None of these facets directly corresponded to the digital media self-efficacy (DMSE) construct used in this study. Therefore, the MKSE 2 facet that most closely aligned with DMSE was selected for prior specification. This scale describes the concrete use of digital media in instructional contexts. The standard deviation was increased to 0.3 for the corresponding parameters to account for the resulting uncertainty in the self-efficacy priors.

For other parameters where no directly comparable examples were found in the literature, moderate regression effects of 0.3 and slightly stronger autoregressive effects of 0.4 were defined as priors based on expert estimates. Experts were full professors focusing on teacher education and specialized in digitalization-related competences of pre-service teachers in the fields of psychology ($n = 1$), science education ($n = 1$), and informatics education ($n = 1$). In the form of a focus group, the three experts were asked to define priors for the respective regression parameters. They were also given insights into the priors defined based on the literature. To quantify the increased uncertainty for these parameters, the respective parameter spaces were expanded by setting their standard deviation to 0.3. The regression coefficients according to Vogelsang et al. (2023) and the hyperparameters used as informative priors can be found in Appendix D.

For variance distributions, a weakly informative Gamma distribution $G(1,1)$ was chosen in regard to the informative priors. All priors were visualized through plots to verify their distributions and assess their plausibility. No multivariate priors, such as those for covariances, were specified in the current model. Given the relatively small sample size, this decision was made to avoid increasing model complexity. Instead, the priors in this path analysis were focused on directed regression paths and variances.

(ii) Test for Convergence

Due to the moderate complexity of the model, model specifications were initially estimated using four MCMC chains with 10,000 burn-in iterations and an additional

10,000 sampling iterations, following the recommendations of Depaoli and Van De Schoot (2017). Subsequently, the MCMC chains were visually inspected for chain convergence via trace plots. To rule out local convergence, a potential shift in distributions after the initial 10,000 iterations, the model specification was rerun with double the burn-in and sampling iterations (20,000 each; Depaoli & Van De Schoot, 2017), and the trace plots were reexamined for any signs of shifts in convergence. Following this, a formal convergence diagnostic was performed. Given the multiple chains, the Gelman and Rubin (1992) diagnostic was employed, utilizing the potential scale reduction factor (PSRF) to assess convergence, with values below 1.1 generally accepted as indicating sufficient convergence (Depaoli & Van De Schoot, 2017).

Overall, visual analysis of the trace plots and Gelman–Rubin shrink factor plots suggests that the model exhibits good convergence and mixing across all parameters. Compared to the regression coefficients, the variance parameters demonstrated slightly slower mixing. In the first step, the parameters' trace plots were analyzed for stability in the estimated parameter space and for local convergence. The trace plots suggest that the chains are well-mixed, with each chain exploring the parameter space effectively and showing no clear trends or drifts in estimated mean over iterations, thereby indicating no signs of local convergence. The four chains for each parameter showed strong agreement in their respective parameter spaces, with no evidence of shifts in the distributional patterns. Subsequently, the Gelman–Rubin diagnostic was calculated and Gelman–Rubin shrink factor plots were analyzed. PSRF point estimates and upper confidence intervals of 1.00 for all parameters, as well as a multivariate PSRF of 1.00, indicate successful convergence of the chains across all parameters. The Gelman–Rubin shrink factor plots revealed that most parameters reached stability within the first 5000 iterations, with variance parameters exhibiting more pronounced initial fluctuations before converging. Additionally, the 97.5% quantiles tracked closely to the median lines, suggesting relatively low uncertainty in the parameter estimates. Given these observations, we proceeded with 10,000 iterations, as no indications of local convergence issues were observed.

(iii) Test for Autocorrelation

Despite the strong convergence diagnostics, the data were further analyzed for autocorrelation to assess the degree of dependency between consecutive samples in the MCMC chains. Autocorrelation plots were generated and visually inspected to determine the lag at which the autocorrelation function (ACF) decays to zero. Based on this evaluation, a decision was made regarding the necessity of thinning the sample.

The ACF values for each parameter decreased rapidly, approaching zero by lag 5. This rapid decay indicates that the chains mixed efficiently, with successive samples becoming largely independent after only a few iterations. Such behavior suggests that the MCMC procedure performed effectively, with no significant autocorrelation issues impacting the reliability of the posterior estimates. Consequently, thinning was deemed unnecessary, as the MCMC samples were already sufficiently independent.

(iv) Posterior Distribution

The distribution of the posterior estimates was evaluated visually for informational content using histograms and kernel density plots. Histograms were explicitly employed to detect gaps in the posterior distribution, as Depaoli and Van De Schoot (2017) recommended. Kernel density plots were utilized because they provide a more comprehensive visualization by incorporating all data points, offering greater informational richness than histograms, and are particularly effective in identifying potential multimodal distributions in the data (Węglarczyk, 2018).

The histograms of the posterior distributions for all parameters were smooth, displaying no gaps or abnormalities. This suggests that a sufficient number of iterations was employed, ensuring reliable posterior estimates (Gelman & Rubin, 1992). Similarly, the kernel density plots exhibited relative smoothness, indicating well-mixed chains with no significant irregularities. Additionally, the kernel density plots showed no evidence of multimodality. However, certain parameters, particularly the variance estimates, showed broader posterior distributions, suggesting higher uncertainty compared to the regression parameter estimates.

(v) Sensitivity Analysis

A comprehensive sensitivity analysis was conducted to evaluate the impact of the specified priors on model estimates. This involved re-estimating the model under two conditions: (1) using non-informative priors and (2) applying various adjustments within the predefined priors. Parameter estimates were subsequently compared to assess the influence of these priors on the model's outcomes. As part of the sensitivity analysis, the priors for the regression coefficients were systematically varied between non-informative and informative settings to examine the effects of these changes on model fit and parameter estimates (De Bondt et al., 2020; Kaplan & Harra, 2024). For the non-informative priors, we selected normal distributions $N(0, 100)$ for the regression coefficients and gamma distributions $G(0.001, 0.001)$ for the variance components. This broad specification was chosen to enable the data to primarily guide the estimation process, minimizing the influence of prior assumptions. Initially, we conducted a comparative analysis between the models estimated with non-informative and informative priors to gain a preliminary understanding of the impact of prior specification on posterior estimates and overall model stability. We examined parameter estimates, credible intervals, and model fit indices to achieve this. To deepen this analysis, individual hyperparameters were varied at the parameter level to explore the specific effects of changes in the priors. Initially, as Depaoli and Van De Schoot (2017) recommended, only the mean hyperparameters were incrementally adjusted in steps of 0.2 (upward and downward). Following this, we varied the standard deviation hyperparameters for the regression priors by estimating models with standard deviations of 0.1 and 0.5 for all priors. Finally, the variance priors were varied between gamma distributions $G(0.01, 0.01)$ and $G(10, 10)$. To compare the parameter estimates across models, we calculated the relative difference in parameter estimates, using the model with informative priors as the reference. Following Depaoli and Van De Schoot (2017), differences of $<1\%$ were classified as minor, $1\text{--}10\%$ as moderate, and $>10\%$ as large. The predictive accuracy of the models was calculated using the Leave-One-Out Information Criterion (LOOIC) and compared across the models. In this context, higher LOOIC values indicate lower predictive accuracy. This criterion was selected for its robustness in scenarios involving small sample sizes instead of other information criteria, such as the widely applicable information criterion (Gelman et al., 2013b; Vehtari et al., 2017). The effective number of parameters (p_{loo}) was also included in the comparison to assess model complexity. A higher effective number of parameters suggests increased model complexity and a higher risk of overfitting (Vehtari et al., 2017).

The results of the sensitivity analysis are as follows:

(1) Comparison with Non-Informative Priors

In conducting a sensitivity analysis to compare the influence of non-informative and informative priors, several notable differences in model fit were observed. In this context, the Leave-One-Out Information Criterion (LOOIC) supports the advantage of the informative priors. The lower LOOIC (569.250) of the informative model compared to the non-informative model (575.056) indicates better predictive performance and generalization.

Moreover, the adequate number of parameters (p_{loo}) is lower in the informative model (14.658 vs. 18.682), suggesting that the informative priors effectively regularized the model, reducing its complexity without compromising fit quality. The LOOIC and p_{loo} values of all models estimated during the sensitivity analysis can be found in Appendix C. Appendix E depicts the estimates for the regression parameters, including the credible intervals of the estimated path models that apply informative versus non-informative priors. The relative differences in the regression parameter estimates between the two models are predominantly moderate ($n = 5$) and, in some cases, large ($n = 3$) or minor ($n = 2$). Differences are substantial between the regression paths of self-efficacy (DMSE(t2)) and motivational orientation (MODM(t2)), as well as between attitudes (PADM(t2)) and motivational orientation (MODM(t2)). Compared to the model applying informative priors, the model with non-informative priors results in higher regression estimates between attitudes and motivational orientation and lower regression estimates between self-efficacy and motivational orientation. Posterior variance parameter estimates can be found in Appendix F.

(2) *Parameter Variation*

The sensitivity analysis revealed varying levels of parameter sensitivity to prior specifications. Regression estimates were particularly affected by changes in the mean hyperparameters of the priors. A variation of ± 0.4 in the mean hyperparameters resulted in predominantly large differences in the regression estimates, while a variation of ± 0.2 led to mostly moderate differences. Variance estimates displayed greater sensitivity to downward adjustments of the regression priors, with mild differences emerging when the mean parameter was decreased, compared to minor differences with an upward adjustment. Variations in the standard deviation of the regression priors generally led to minor differences in the variance estimates but caused moderate to significant differences in the regression estimates. This suggests that the precision of the priors (as reflected by their standard deviations) had a substantial impact on the forecast, particularly on the regression coefficients. Finally, variations in the variance priors, specifically between $G(0.01, 0.01)$ and $G(10, 10)$ distributions, resulted in minor differences in the regression estimates but moderate to large differences in the variance parameters.

When comparing the LOOIC values across the sensitivity analysis, the baseline model with the original informative priors demonstrated the second-best fit among all models tested, indicating that the original informative priors provided a robust foundation for model estimation. Regarding model complexity, as indicated by the effective number of parameters (p_{loo}), the baseline model was of average complexity relative to the other models. Notably, the model employing a low, uniform standard deviation in the regression priors ($SD = 0.1$) achieved the best overall fit, with the lowest LOOIC and the most straightforward model structure, as evidenced by the effective parameters. However, it is important to note that while the model with $SD = 0.1$ produced superior fit metrics, the strict constraints imposed by such a low standard deviation could overly restrict the model's flexibility, particularly for the small sample size ($n = 42$). This raises concerns that the model may excessively rely on priors, some of which are guided by somewhat uncertain expert estimates. Therefore, while the model is promising, caution should be exercised in interpreting these results, as the small sample size may not support the stringent assumptions embedded in such narrowly defined priors.

(3) *Evaluating Model Fit*

We used the Posterior Predictive P-Value (ppp) and the Bayesian Root Mean Square Error of Approximation (BRMSEA) to evaluate model fit. The ppp, following the principles of posterior predictive checking, was particularly appropriate due to its reliability in small

samples, with a value around 0.5 indicating good fit (Gelman et al., 2013a). Although the BRMSEA is typically used in large samples, we included it to provide an additional perspective on model fit. As noted by Hoofs et al. (2018), this fit index can be unstable in small samples. Despite this limitation, the BRMSEA was employed, with values below 0.05 indicating good fit and those between 0.05 and 0.08 considered acceptable (Hoofs et al., 2018). By combining ppp and BRMSEA, we sought to balance the ppp's strength in small samples with the broader evaluation offered by BRMSEA, while remaining cautious of its limitations in this context.

Appendix C

Leave-One-Out Information Criteria (LOOIC) and effective number of parameters (p_{loo}) of the estimated models.

	LOOIC	p_{loo}
Informative Priors (Baseline Model) N(M, SD), G(1, 1)	569.250	14.658
Non-informative Priors	575.056	18.682
M (−0.4)	574.103	14.340
M (−0.2)	570.807	14.527
M (+0.2)	569.754	14.876
M (+0.4)	572.067	15.166
SD = 0.1	564.003	9.585
SD = 0.5	572.386	16.803
G(0.01, 0.01)	570.505	15.765
G(10, 10)	570.989	11.253

Appendix D

Selected hyperparameters of the informative priors for regression paths in the model.

	Regression Coefficient According to Vogelsang et al. (2023)	Hyperparameters of the Informative Priors for Regression Paths in the Model
MODM(t2)~MODM(t1)	0.345	N(0.4, 0.2)
MODM(t2)~PADM(t2)	0.335	N(0.3, 0.2)
MODM(t2)~DMSE(t2)	0.323	N(0.3, 0.3)
DMSE(t2)~DMSE(t1)	0.395	N(0.4, 0.3)
PADM(t2)~PADM(t1)	0.495	N(0.5, 0.2)
DMSE(t2)~VEDM(t2)	-	N(0.3, 0.3)
PADM(t2)~VEDM(t2)	-	N(0.3, 0.3)
VEDM(t2)~VEDM(t1)	-	N(0.4, 0.3)
FUDM(t2)~MODM(t2)	-	N(0.3, 0.3)
FUDM(t2)~FUDM(t1)	-	N(0.4, 0.3)

Appendix E

Posterior regression parameter estimates and credible intervals in Bayesian path modeling of the estimated path model with informative and non-informative priors.

Regression Parameter		MODM (t2)	MODM (t2)	MODM (t2)	PADM (t2)	PADM (t2)	DMSE (t2)	DMSE (t2)	VEDM (t2)	FUDM (t2)	FUDM (t2)
		MODM (t1)	PADM (t2)	DMSE (t2)	PADM (t1)	VEDM (t2)	DMSE (t1)	VEDM (t2)	VEDM (t1)	FUDM (t1)	MODM (t2)
Model with Informative Priors											
Regression		0.419	0.517	0.165	0.438	0.202	0.492	0.115	0.494	0.417	0.307
Credible Intervall/ Posterior Intervall	lower	0.217	0.257	−0.031	0.241	0.066	0.278	−0.085	0.200	0.165	0.051
	upper	0.618	0.766	0.369	0.639	0.337	0.703	0.318	0.788	0.666	0.563
Model with Non-Informative Priors											
Regression		0.402	0.680	0.104	0.419	0.199	0.512	0.088	0.522	0.420	0.308
Credible Intervall/ Posterior Intervall	lower	0.166	0.354	−0.188	0.195	0.061	0.283	−0.131	0.180	0.131	0.018
	upper	0.634	10.006	0.324	0.642	0.335	0.744	0.307	0.863	0.706	0.598

Appendix F

Posterior variance parameter estimates and credible intervals in Bayesian path modeling of the estimated path model with informative and non-informative priors.

Variance Parameter		MODM (t2)	PADM (t2)	DMSE (t2)	VEDM (t2)	FUDM (t2)
Model with Informative Priors						
Variance		0.495	0.423	0.946	10.679	10.004
Credible Intervall/ Posterior Intervall	lower	0.319	0.274	0.612	10.098	0.650
	upper	0.423	0.946	10.452	20.568	10.538
Model with Non-Informative Priors						
Variance		0.467	0.396	0.948	10.725	10.015
Credible Intervall/ Posterior Intervall	lower	0.297	0.254	0.607	10.110	0.649
	upper	0.733	0.617	10.476	20.660	10.579

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Article

Evaluating the Effectiveness of an Extracurricular Teacher Education Training Program for DigCompEdu Competences

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Abstract: In the ongoing era of digital transformation, it is imperative for teachers to equip learners with essential digital competences to navigate the intricacies of the digital landscape successfully. As future in-service teachers function as role models and educators for the proper use of digital technology, pre-service teachers must develop adequate digital proficiency. This holds particularly true in Germany, where the prevailing competence levels of pre-service teachers are reportedly suboptimal. To this end, an extracurricular training program for pre-service teachers, based on the DigCompEdu framework, was implemented from 2021 to 2024, coinciding with COVID-19 pandemic-related limitations. A total of 242 pre-service teachers registered for the program, and 40 completed it. Employing a pre–post design, we assessed (1) attitudes towards digital technology and digital learning, (2) competence beliefs, and (3) test-based competences. Pre–post comparisons show an improvement only in participants’ confidence in deploying digital technologies for subject-specific purposes. Unexpectedly, no other statistically significant differences were observed. These findings point at shortcomings in the program, which are discussed to highlight potential areas for refinement and improvement in future programs and curricular implementation.

Keywords: teacher education; pre-service teachers; digital proficiency; DigCompEdu; digital competence; COVID-19; online training program

1. Introduction

1.1. Research Context

Teachers are central to learning in schools [1,2]. Learning in schools aims to prepare students to be effective participants in society. To participate effectively in society, the culture of the target society should be adapted. The culture of the current society is largely and still acceleratingly based on digital technologies [3]. To adapt to a culture that is based on digital media to participate effectively in the society that it is based on, digital competences are needed. Therefore, it is of the utmost importance that teachers use contemporary technologies competently [4]. The benefits are at least twofold. Students mimic the required digital competences by witnessing their teachers using digital technologies [5], and digital technologies can enrich learning and teaching processes if used competently by optimizing these processes in effectiveness and efficiency [6]. However, the education sector faces significant challenges in the adaptation to digital technologies effectively, particularly in Germany [7,8]. This has become especially apparent during the Emergency Remote Teaching (ERT) [9] period prompted by the COVID-19 pandemic [10].

Even before the pandemic, large-scale studies showed that less than 40% of European educators felt prepared to use digital technologies in teaching [11]. Pre-service teachers in Germany showed a greater need for support in acquiring digital skills and fostering favorable attitudes toward technology compared to other students [12]. More importantly,

according to the German National Educational Panel Study (NEPS; N = 1766), which measured ICT Literacy (domains in an educational context: Search and Organize, Assess, Create, Communicate, Apply, and Understand) in forms of competence beliefs and simulation-based performances, about two-thirds of pre-service teachers did not meet expertly defined minimum digital competence standards towards the end of their studies [13]. This highlights a significant gap in digital readiness. Understanding these effects is crucial, especially given the rising demand for digital competence in education due to contemporary large-scale funding, e.g., German policy initiatives to equip schools with digital infrastructure and equipment. Therefore, it is necessary to address these shortcomings in teacher education accordingly.

In Germany, however, approximately 25% of teacher education curricula still neglect digital competences [14]. Hence, 28% of teacher education institutions offer extracurricular opportunities to foster digital competences among pre-service teachers, serving as a transitional step toward curricular integration [14,15]. These programs aim to equip future educators with the necessary digital competences to integrate technology effectively into their teaching practices, but to facilitate their successful curricular implementation, empirical validation is necessary. Otherwise, teacher education structures risk inadequately addressing the factual needs and practical challenges faced by teachers in increasingly digital learning environments.

While these extracurricular courses have been introduced, little is known about their actual impact on participants' competences and attitudes. Thus, this study will evaluate an extracurricular training program for pre-service teachers at a German university. Building on the DigCompEdu framework [16], the program in question provides a structured approach to competence development. However, to inform the eventual curricular implementation empirically, it remains to be tested how the program translates into improved competences and favorable attitudes, both of which are essential for effective technology integration in the classroom [17].

1.2. Theoretical Background

The primary focus of the present study is on competence. For the theoretical conceptualization employed in this paper, competence is “the ability to perform to a specified standard” [18]. On the one hand, this entails a criterial norm to evaluate the quality of the performance. On the other hand, since an ability denotes a potential performance, it is a latent construct that remains unclear how to measure it validly and reliably. Hence, two different approaches emerged to measure competence: To observe and evaluate performance per se is an authentic approach, in which it remains unclear if the observations capture what a person is capable of. In contrast, an analytic approach would be to measure the dispositions of a person as a premise to predict performance, in which it remains unclear if everything relevant is accounted for concerning a precise prediction. A holistic framework that combines both approaches is the “competence as a continuum” model [19]. In it, competence is conceptualized by four elements: (1) cognitive dispositions, (2) affect-motivational dispositions (e.g., attitudes), (3) situational specificity, and (4) performances. Different definitions of competence consider various elements in their modeling. The (1) and (2) dispositions are personal premises to interact with (3) a specific situation for a competence to be expressed as in (4) observable behavior.

Despite the integration of attitudes into competence models, established instruments for measuring educators' digital competences mostly separate competences from attitudes. Consequently, in this study, using established instruments, competences, and attitudes will be measured accordingly.

1.2.1. Attitudes Towards Technology

Attitudes as part of the affect-motivation competence disposition are central to the concept, as they define a tendency to respond favorably or unfavorably to the object in question [20]. Attitudes towards technology were established in the Technology Accep-

tance Model (TAM) [21] to originally predict technology use, but they have also been used successfully to predict teachers' use of digital technology in their teaching practices [22]. Perceived usefulness (PU) and ease of use (EOU) are the indicators for attitudes towards technology. These concepts of indicators have been adapted and expanded for the educational context. For example, ease of use has been redefined in terms of perceived costs [23]. Furthermore, next to perceived usefulness, perceived importance and interest [23], along with hedonistic and instrumental use incentives [24], have been added for more differential views.

However, research using the TAM traditionally looks at technology use regarding how frequent the use is but not how successful. An established model that also addresses the quality of use is the Will–Skill–Tool Model [17], which empirically validates the hypothesis that successful implementation of technology in teaching practices requires not just ATT but also respective competences and tools.

1.2.2. Digital Competence of Pre-Service Teachers

Regarding technological competence for teachers, the DigCompEdu framework is state of the art for European countries and is thus predominantly used as a guideline for teacher training programs. For an overview, it is illustrated in Figure 1.

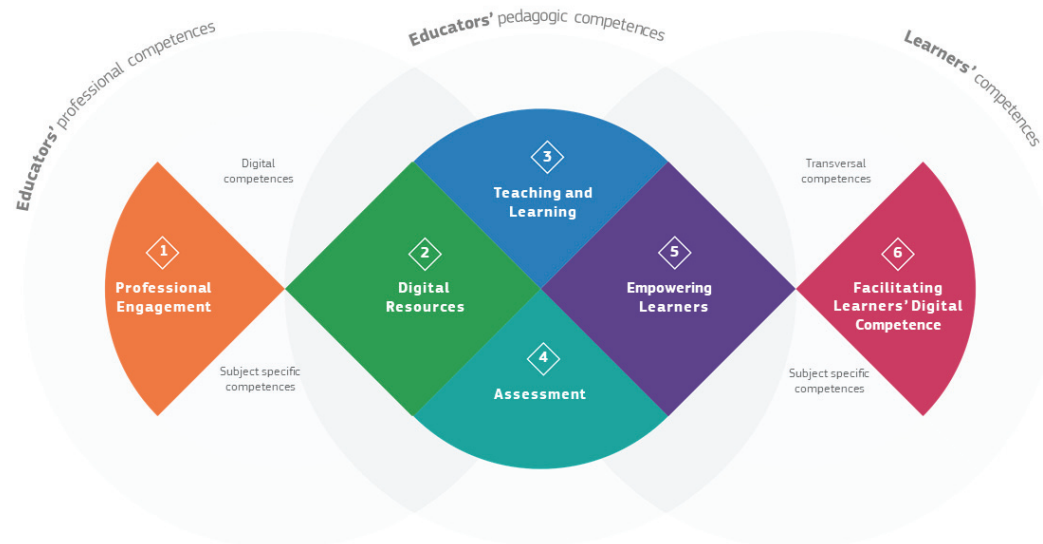


Figure 1. The DigCompEdu framework [16] (p. 15). © European Union, 2017. Licensed under CC BY 4.0.

It identifies six competence areas for the professional use of technology as follows: (1) Professional Engagement, which involves using digital tools for communication, collaboration, and professional development; (2) Digital Resources, focusing on sourcing, creating, and managing digital content responsibly; (3) Teaching and Learning, where educators integrate digital technologies to enhance instructional methods and learner engagement; (4) Assessment, which includes leveraging digital tools to assess, provide feedback, and adapt teaching strategies; (5) Empowering Learners, aimed at using digital tools to support personalized learning and inclusivity; and (6) Facilitating Learners' Digital Competence, enabling learners to develop skills in information literacy, digital collaboration, and responsible technology use [16]. Although the content of the program evaluated in this paper was theoretically grounded on DigCompEdu, there were no adequate instruments available to measure DigCompEdu competences, which is why it was necessary at the time of this study to utilize other frameworks.

The Technological Pedagogical and Content Knowledge (TPACK) model is one of the most well-known frameworks in international research [6]. It expands Shulman's classical Content Knowledge (CK), Pedagogical Knowledge (PK), and Pedagogical Content Knowledge (PCK) model [25] by adding Technological Knowledge (TK). The TPACK model

also describes intersections between TK, PK, and CK, resulting in additional domains such as Technological Pedagogical Knowledge (TPK), Technological Content Knowledge (TCK), and TPACK itself [6]. The hierarchical structure of the model assumes that TPACK is rooted in TK, which interacts with PK and CK over time to form TPK and TCK, which in turn form the foundation for TPACK.

TCK refers to understanding how technology and subject content influence each other. TPK describes knowledge about the existence, components, and capabilities of various technologies used in teaching and learning environments, and TPACK modules these domains, enabling teachers to use technology in ways that meet specific pedagogical and content-related demands.

In the German educational context, “media pedagogy” is an umbrella term for education with digital technology. Amongst other competence areas, media pedagogical competence was operationalized by Technical Knowledge, which refers to understanding and utilizing media technologies in teaching and learning processes; media literacy education, focused on fostering responsible, creative, and critical media use by learners, including knowledge of media effects and legal, social, or ethical aspects; and media education, which involves the planning, execution, and evaluation of lessons that incorporate media to enhance learning outcomes [26,27]. The competence areas were chosen in accordance with the program contents.

In summary, the TPACK and Media Pedagogy frameworks primarily cover digital resources, teaching and learning, and facilitating learners’ digital competence of the DigCompEdu framework. However, they fall short in addressing the other domains of Professional Engagement, Assessment, and Empowering Learners.

1.2.3. Facilitating Factors for Competence Development

With a view to predicting success in preparing pre-service teachers for technology use, the Synthesize Qualitative Data (SQD) model provides a comprehensive framework built around seven strategies [28]. Training programs should (1) link theory with practical application. By aligning theory and practice, pre-service teachers can see the relevance of technology in real teaching contexts, easing the transition from learning to implementation. (2) Teacher educators should serve as role models, demonstrating effective technology use and inspiring confidence in future teachers. (3) Reflective practices should be utilized to help pre-service teachers explore their attitudes toward technology, fostering openness and adaptability. (4) Training programs should emphasize the use of digital technology for instructional design to help teachers integrate technology in transformative ways. (5) Peer collaboration should be encouraged to offer a supportive space for sharing ideas and reducing anxiety. (6) Authentic, hands-on technology experiences should be implemented to build confidence in real classroom settings. Finally, (7) continuous, formative feedback should be provided to encourage ongoing growth and refinement of skills [28].

Beyond the elements outlined above per se, there is also empirical evidence for interactions [29,30]. Thus, teacher educators as role models provide examples that spark reflection, prompting pre-service teachers to examine their own attitudes towards technology. This reflective process is further enriched through peer collaboration, where shared insights build confidence and adaptability. The emphasis on instructional design is reinforced when pre-service teachers apply their plans in authentic, holistic, hands-on experiences, offering real-world validation and practical refinement. Continuous formative feedback amplifies the benefits of these experiences by providing timely insights, helping pre-service teachers adjust their designs and deepen their practical skills. Together, reflection and feedback support pre-service teachers’ growth, while collaboration and hands-on learning offer a supportive framework that aids competence development [29,30]. Hence, empirical evidence shows that the implementation of SQD strategies predicts TPK and TPACK [31–33].

1.2.4. Study Aims

The contemporary landscape of pre-service teacher training for digital competences reflects a complex interplay of methodological, contextual, and pedagogical variables. Meta-studies highlight significant heterogeneity in program structure (e.g., curricular or extracurricular), cultural context (e.g., Western or Eastern), content (e.g., different competence framework orientations and selective domain addressing but also theoretical vs. practical orientation), teaching environment (e.g., online or offline), and measurement instruments (e.g., competence beliefs or knowledge tests), which collectively present challenges to determining the overall effectiveness of training programs aimed at building digital competences of pre-service teachers [34–36]. This variability limits the comparability and generalizability of findings across programs and requires differentiated findings for more clarity on the causes of effects [34,35].

Meta-analyses implicitly emphasize the importance of SQD strategies in fostering digital competences among pre-service teachers, yet substantial inconsistencies in how these strategies are implemented create further challenges for the comparability of effects amongst programs [35,36]. Without consistent application of all SQD strategies, programs frequently fail to facilitate competence and confidence in technology integration [35,37–39]. Empirical evidence suggests that the strategies of authentic, hands-on experiences and role models are more central to competence development due to their foundational role in contextualizing theoretical knowledge, feedback, reflection, and peer collaboration, serving as a first-hand experiential basis for future teaching practices [15,29,30].

In conclusion, the aim of this study is to inform an international research context with a German perspective, which is about empirically informing the ongoing curricular implementation process in teacher education. The following research question guided the investigation: What are the effects of a self-directed, extracurricular, DigCompEdu-oriented online training program with limited SQD strategy implementation on the progression of digital competences and attitudes of pre-service teachers at a German university?

Based on the program's contents, it was hypothesized that competence beliefs, test knowledge, and attitudes would increase statistically significantly, i.e., for attitudes, and that the perceived costs of using technology for teaching would decrease while all other measures, except for the incentive for hedonistic use, would increase.

2. Methods

2.1. Sample

The data for this study were collected through surveys in a pre–post design for the training program. The survey was pseudonymized, i.e., students were assigned a random identification code at the pre-measurement, which they reused for the post-measurement to enable longitudinal analysis. Ethical approval was not sought from an institutional review board, as this study adhered to the principles of good scientific practice outlined by the operating university and the German Research Foundation (German DFG), which requires minimal risk to participants. Participation in the training program was voluntary, and the requirement to take a pre- and post-survey was communicated explicitly and beforehand to each participant; the program and the surveys did not include any invasive procedures; the pseudonymization of data ensured participants' privacy in accordance with the General Data Protection Regulation (German DSGVO); and all participants provided informed consent before data collection and were assured of their right to withdraw from this study at any point without consequence. Ergo, the research was exempt from ethical approval by the university senate's ethical committee.

The sample for the registered participants consisted predominantly of Bachelor of Education (B.Ed.) students and a smaller proportion of Master of Education (M.Ed.) students at a predominantly humanities university (see Table 1). They were mainly female, in their twenties, and halfway through their course of studies. Among the 242 registered participants, 40 students (16.5%) completed the training program. They took an average of 2.3 half-year terms $\pm$ 1.1 to finish the course content. The starting and ending points of the

measurements range from the winter semester of 2021/2022 to the summer semester of 2024. Thus, the measurements largely took place throughout the COVID-19 pandemic, in which protective measures officially ended in April 2023 in Germany.

Table 1. Sample overview.

	Registered	Completers	Non-Completers
N	242	40	202
Age	24.5 ± 5	24.6 ± 5.9	24.5 ± 4.8
Gender	167 ♀; 74 ♂	31 ♀; 9 ♂	136 ♀; 65 ♂
Semesters studied	4.5 ± 2.4	4.9 ± 2.4	4.5 ± 2.4
B.Ed./M.Ed.	166/76	25/15	141/61

Given the low completion rate of 16.5%, it is also relevant to investigate conditions that facilitated the completion of the program. Controlling for a systematic dropout bias by comparing completers to non-completers did not yield significant differences in gender $\chi^2(1, 242) = 1.518$ $p = 0.21$, age ($p = 0.945$, $d = 0.012$), or in progress in studies upon beginning the program ($p = 0.355$, $d = 0.160$). Likewise, measures for competence beliefs, test knowledge, or attitudes did not differ significantly between groups. That said, potential differences amongst these groups in parameters not assessed within the scope of this study (such as, for example, personality traits or self-efficacy beliefs) cannot be ruled out based on the available data.

In a previous study within the same project addressing facilitating conditions for this program's registrations [40], differences between registered and non-registered pre-service teachers have been analyzed. As there are no significant differences between completers and non-completers of this study within the same project, those differences can provide a point of reference to a broader pre-service teacher population ($N = 392$). Compared to pre-service teachers who did not register for the program, registered participants perceived teaching with digital technology to be more important and interesting, did not believe as much in their competences regarding TK and TCK, and scored higher on every knowledge test, but there was still with potential to improve [40].

As a response to the rather low completion rate, one person who completed and one person who did not complete the program were interviewed about their participation experience concerning the integration of SQD strategies and other strengths and limitations. The interviewee who did not complete the training program finished the first three modules that mainly addressed aspects of TK (see Figure 2).

	Content	Workload
Module 1	Basics of digital teaching and learning	10h
Module 2	Basics of information technology	10h
Module 3	Legal aspects of digital teaching	8h
Module 4	Media didactics and media pedagogy	10h
Module 5	Media education	10h
Module 6	Digital media in teaching	10h
Module 7	Digital teaching materials	8h
Module 8	Promoting digital learning	8h
Module 9	Communication and collaboration	8h
Module 10	Digitalization and society	8h

Figure 2. Competence of the training program and estimated workload in hours (h).

2.2. Training Program

2.2.1. Project Parameters and Training Program

To put the training program into context, it is necessary to briefly describe how teacher education is structured in Germany. Teacher education in Germany is divided into two

stages. The first chiefly theory-oriented stage is a university-based combined B. Ed./M. Ed. program that roughly lasts five years, where students undergo studies in the two content domains that they are to teach later, alongside an extensive educational science curriculum embracing four modules on “education”, “teaching”, “assessment”, and “innovation”. Obtaining a M. Ed. degree therein grants access to the second, more practical, preparatory service’ stage, typically lasting one-and-a-half years, which is no longer supervised by the university but is in the hands of ministry-run training institutes. After succeeding in the second stage, teachers are fully qualified to work in schools, without any further high-stakes evaluation. The training program described in this paper is situated within the first stage of teacher education, as digital competences are [still] underrepresented in current curricula. It is decidedly a voluntary offer that students can take part in on top of their regular studies.

The training program was embedded into a larger project. It was funded by the Federal Ministry of Education and Research as part of a national initiative to improve teacher education in the context of digitalization (funding period 2020–2023). Thus, it was developed during the pandemic and took place during 2020–2024, including the COVID-19 lockdown-laden years (the program was conceptualized to go beyond the funding period). The project concentrated on establishing digitalization in teacher education so that students understand digital education as an indispensable element of their own professionalization process. It, therefore, aimed to further develop teacher training in the field of digitalization. The project focused on competent teaching with digital media in the same way that it emphasized the reflection and critical examination of digital transformation and its social consequences.

The development of the training program was central to the project. Students could take part voluntarily during their compulsory studies within their teacher education. The training program was open to all pre-service teachers at the university, regardless of their teaching subjects or pursued school type. Thus, the training program was not subject specific but primarily addressed interdisciplinary issues relating to digitalization. No prior knowledge of the topic of digitalization was required to be able to participate. There was also no limit to the number of participants.

The training program consisted of a total of ten modules that were built on each other chronologically (see Figure 2 for an overview of the content). The necessary workload to complete the training program is estimated to be 90 h. It was designed as a self-directed study course with no synchronous appointments offered. This means that the students took primary responsibility for their learning process without direct instruction or monitoring from teachers. Thus, students could make their own decisions about how, when, and where they studied. Regarding the schedule, there was no time limit in which the modules had to be completed to allow for maximum flexibility while working on the training program simultaneously. The decision to carry out the training program without face-to-face teaching elements was mandated by the COVID-19 pandemic circumstances. Therefore, a pragmatic decision had to be made to offer students a training program that they could complete without ever being present at the university. For this reason and for resource optimization, the training program has been implemented as a digital self-study course with a regional Learning Management System (LMS) licensed by the operating university.

2.2.2. Contents, Schedule, and Methodology of the Training Program

Since the training program was designed as a digital self-study course, students could work on the courses independent of time and location to ensure maximum flexibility in a self-directed online learning arrangement. The structure of the modules was identical across subjects, although subject-specific references were made for the individual subjects. Each module consists of several chapters.

As it was based on the DigCompEdu framework, the training program was normatively framed and oriented towards European frameworks and standards on digital competences for teachers. Consequently, the training program was created in a top-down

approach. The first module of the program (basics of digital teaching and learning) was designed as an introduction, beginning with novice-level knowledge. Pre-service teachers were introduced to the question of how digitalization affects educational processes and goals. They were also introduced to possible applications of apps and learning platforms as well as questions about IT equipment in schools. Moreover, criteria for evaluating digital resources were discussed. This module aligns with the second competence area of the DigCompEdu “digital resources” in which selecting, identifying, and assessing digital resources to support and enhance teaching are the main competence areas to be fostered in teacher education. Additionally, teachers needed to critically evaluate the credibility and reliability of digital resources and assess the usefulness of these tools [6,16].

The second module focused on the basics of information technology and contained learning modules on hardware and software components, computer networks, basic elements of programming, and data privacy, summarized as computer literacy. Students were thus introduced to how technology works to foster their TK. As learners need to acquire digital skills, it is essential for teachers themselves to understand digitalization from a technological perspective. Teachers’ digital competences are thus a prerequisite for learners to acquire them as well. Although DigCompEdu does not explicitly describe computer literacy as a separate competence area, computer literacy is associated with selecting digital resources and teaching and learning in the digital age (competence areas 2 and 3). This affects both the ability to select and adapt appropriate digital technologies and resources for teaching and the understanding of how these can process, represent, and influence information.

Module 3, legal aspects of digital learning, provided an overview of data protection and personal rights as well as copyright law, targeting TK as well. This was supposed to help master the balancing act between legal restrictions and the needs of everyday school life. With the help of case studies, students assessed legal issues in specific school situations to discuss the duties and rights of students as well as teachers when it comes to media integration. This aligns with competence area 1 in the DigCompEdu (Professional Engagement), as it emphasizes the importance of understanding and respecting ethical and legal norms concerning the use of digital technologies and digital content as a core digital competence of teachers.

Whereas modules 1–3 deal with the information technology and legal aspects of digitalization, modules 4 and 5 deal with pedagogical–methodological principles and media education. Modules 4 and 5 are also aimed at TPK. The modules also correspond to competence area 6 of the DigCompEdu, in which facilitating a learner’s digital competence is described as a core competence of the teaching profession in the 21st century. Specifically, modules 4 and 5 cover different approaches to teaching and learning with digital media and deal with the question of which digital competences learners need to become responsible citizens in the digital age. Additionally, students learned about various media education concepts and evaluated them for their future school practice. They also received hands-on examples of how to implement them in the classroom.

The most practical course modules are modules 6, 7, and 8. These were based on competence areas 2–4 in DigCompEdu and were oriented towards selecting, creating, planning, and implementing digital resources for learning, which is considered a key competence of the teaching profession [16]. Moreover, pre-service teachers received input towards the potential of digital media for collaborative learning and game-based learning and got to know a collection of digital resources to use in the classroom. In module 7, for example, students got to know what textbook publishers offer in terms of digital textbooks or accompanying materials. With the use of teaching videos, module 8 also covered the quality criteria of teaching with digital media. In alignment with DigCompEdu, modules 6, 7, and 8 focused on teachers’ competence to implement digital resources to effectively foster learning processes. These competences are covered as TPK [6]. The program could not target TCK and TPACK because of a lack of resources to cover all offered subject-specific didactics at the university.

Lastly, modules 9 and 10 addressed forms of digital communication and the question of how human communication changes due to increasing digitalization processes. Module 10 specifically analyzed digitalization from a social perspective and explored what these transformation processes mean for societies. Reflecting on the consequences for schools is also part of module 10. With these two modules, pre-service teachers' professional digital competences were expressed by their ability to use digital resources to interact with colleagues or students, etc. (see DigCompEdu competence area one: Professional Engagement).

2.2.3. Learning Goals of the Training Program

The design of the modules was based on comprehensive pedagogical and methodological planning. For each module, learning objectives were formulated in advance to provide students with a transparent understanding of the objectives to be achieved in each course. This was supposed to enhance students' motivation to engage in the content provided. The courses have been designed as learning paths, meaning that the chapters were built on each other and were unlocked as soon as one had completed the previous chapters. The SQD model served as a guiding framework for the design of the training program since it provides a comprehensive framework for training programs aiming at digital competence development [28]. At this point, it is already important to stress that the format of the training program as a digital self-study course did not allow for the implementation of all SQD strategies with all its facets. Since the consistent application of all SQD strategies might be crucial for competence development, these shortcomings will be discussed later.

Regarding the SQD strategies, research has shown that authentic and hands-on learning experiences are most crucial. This strategy is closely linked to offering students practical learning experiences to bridge the gap between theory and practice. According to the SQD model, approximation of practice is a central principle in technology integration courses since students need practice-oriented authentic experiences, such as lesson planning phases and hands-on experiences, to become competent in technology integration [28]. Especially, in the more practical modules (6–8) of the training program, participants had the chance to design digital teaching materials and work with lesson videos to be analyzed [28]. This offered students the opportunity to work in an action-orientated way. Additionally, the modules offered students the chance to get to know various software tools to be used in the classroom.

Closely linked to the strategy of implementing practical and authentic learning experiences is the strategy of implementing an instructional design in the SQD model. (Re-)designing technology-enhanced teaching materials is another promising strategy for pre-service teachers to develop digital competences [28]. More precisely, engaging students in lesson planning and providing additional preparation in instructional design to implement technology could affect competence development [28]. This strategy was realized in the training program by discussing didactic principles of lesson planning with digital media and reflecting upon different forms of learning with digital media. Students in the training program not only had the chance to engage with theoretical input on instructional design but also had the chance to design their own teaching materials based on the theoretical input they received. For example, they were asked to design a short digitally mediated learning situation in their subject and describe the learning objectives of the task. With respect to digital teaching materials, students had the chance to work with digital versions of schoolbooks and analyze teaching materials according to methodological and didactical criteria.

Moreover, collaboration is central to developing digital competences [28]. Since the training program was self-directed without face-to-face teaching, collaboration phases were shifted into the digital environment using forums and wikis as a place for students to share ideas and prior experiences with digital media. Students could comment on each other's ideas and engage in different discussion questions using forums or digital tools, such as

Padlet or Flinga. Additionally, students were asked to share digital resources and teaching materials with peers.

According to the SQD model, reflection is also essential for competence development. Our training program aimed to realize this strategy by incorporating an e-portfolio to enable students to reflect upon their learning process. In the e-portfolio, students could choose between several tasks to work on in depth. All of the tasks dealt with the content provided in each of the modules and allowed for a deeper examination of the content. Reflection tasks, for example, were included to help students critically reflect upon the importance of digital competences in today's society.

Additionally, feedback was provided in an online format, and the training program included several quizzes and free text answer options to check for understanding.

Lastly, to implement role models, students were asked to view videotaped classroom teaching episodes. In these videos, teachers used digital media and were filmed. Students were asked to analyze the teaching performances regarding teachers' and student' reactions and interactions, the perceived competence development, and the intended goals of media usage. Using classroom videos was linked to the goal of encouraging students to use technology and pick up techniques by observing other teachers in action.

In summary, the training program incorporated most of the SQD strategies to foster digital competence among pre-service teachers, though each was adapted due to the pandemic and project circumstances, resulting in an online format of the training program. Aligning theory and practice was achieved by lesson planning tasks and analyzing teaching materials. Instructional design allowed students to create digital teaching materials. Role modeling was provided through pre-recorded classroom videos. Collaborative learning opportunities were provided in the form of discussion questions in digital forums. Reflection was encouraged via e-portfolio tasks, whereas feedback was mainly provided via quizzes.

2.2.4. Execution of the Training Program

The training program was administered by members of the university's teaching staff who developed its contents (trained certified subject-matter experts). Students could contact the administrators with questions at any time via email. Administrators provided technical support but also helped with content-related questions about the modules. Participants of the training program first had to register on the LMS and complete the pre-survey to be activated for each of the ten modules by the administrators. Students were advised to start working on the first module and to continue working on it chronologically. When the participants finished the training program (completion of all ten modules and the e-portfolio), they had to send an email to the administrator who checked for completeness. If the modules and the e-portfolio were successfully completed, students received a confirmation email.

Students who were interested in the training program could register twice a semester. The acquisition of participants took place in three steps: (1) contacting the students, (2) a meeting in which interested students were informed about the training program, and (3) a meeting in which registered students received detailed information on the training program. In the first step, several advertising channels were used to reach as many students as possible. Students could receive information via a dedicated homepage and were contacted via the internal university e-mail distribution list. Additionally, social media channels (especially teacher-related institutional Instagrams) were used as advertising measures. Secondly, the aims, structure, and content of the training program were explained in an online meeting to those students who were interested in participating. It was advertised that the competent use of digital media is a key skill in the 21st century and is, therefore, a central competence of a teacher's professional life. Students were informed that the training program offers an additional professionalization opportunity in the field of digitalization and enables students to acquire theoretical and conceptual knowledge regarding digitalization in school. In the third step, all students who had registered for the certificate were invited to an online meeting to be introduced to the specific organization

and content of the training. Emphasis was placed on how the LMS works and what is expected from the participants in terms of requirements. After this introductory session, participants could register in the LMS. Participating in the training program was mainly dependent on students' intrinsic motivation since there were no extrinsic incentives, such as a meaningful certification for their teaching.

2.3. Instruments

This study employed multiple instruments to assess cognitive and affective–motivational dispositions of digital competences, i.e., competence beliefs and test-based knowledge for the former and attitudes for the latter. All scales are positively keyed, meaning high numerical values indicate high endorsement. Regarding the operationalization of digital competences, ongoing discussions revolve around the validity of competence beliefs compared to knowledge or performance tests [41,42]. As a result, both competence beliefs and knowledge tests were administered in this study. However, the knowledge test items might not completely overlap with the contents of the program but were still utilized and were unadapted for comparable results. It was assumed that the knowledge from the program could be extrapolated onto items that were not explicitly subject to it.

Competence beliefs were utilized based on TPACK.xs [43], measuring constructs such as TK, TPK, TCK, and TPCK. Knowledge tests were administered for Media Pedagogy [27] and TPK [41]. Some scales for attitudes were related to prospective teaching practices and included dimensions, like usefulness, interest, importance, and cost [23]. Additionally, computer-related incentives were measured to explore instrumental and hedonistic incentives [24]. A detailed overview of the instruments with examples, item counts, metrics, and internal consistencies is provided in Table 2. Cronbach's alpha is acceptable for most instruments ($\alpha > 0.7$), except for the test-based knowledge instruments for Media Literacy Education, Media Didactics, and Conceptual TPK Knowledge.

Table 2. Instrument overview.

Construct [Source]	Subscale	Example Item	I _n	Metric	α
TPACK [43]	TK	I know about many different technologies.	4	1–5	0.92
	TPK	I can adapt the use of technologies that I am learning about to different teaching activities.	4	1–5	0.78
	TCK	I can explain which technologies have been used in research in my field.	4	1–5	0.83
	TPACK	I can select technologies to use in my classroom that enhance what I teach, how I teach, and what students learn.	4	1–5	0.84
Media Pedagogy Knowledge [27]	Technical Knowledge	What does storing files in the cloud mean?	26	0–26	0.81
	Media Literacy Education	Regarding media literacy, which statement is most likely to apply to the justification of largely free media access?	17	0–17	0.57
	Media Didactics	Do extracurricular television habits have any significance for learning with a video?	22	0–22	0.58

Table 2. Cont.

Construct [Source]	Subscale	Example Item	I _n	Metric	α
TPK Knowledge [41]	Situational Knowledge	Please mark the teaching processes for which you think the respective technology can be used in the classroom to promote student learning.	12	0–96	(0.86)
	Conceptual Knowledge	Digital information and communication technologies for coaching, and communication offer the potential that . . .	8	0–32	(0.41)
	Perceived Usefulness	The use of digital media in teaching has advantages for teachers.	3	1–5	0.79
Attitudes [23]	Interest	Using digital media in teaching will be fun for me.	3	1–5	0.90
	Importance	The use of digital media in teaching will be an important part of my role as an educator.	3	1–5	0.86
	Cost	To use digital media in the classroom, I would have to give up other activities.	3	1–5	0.71
Computer-related Incentives [24]	Instrumental	I use computers and the Internet to create texts or presentations as part of my work or training.	7	1–4	0.81
	Hedonistic	I use my computer and the Internet to watch movies and videos.	7	1–4	0.87

I_n = item count. α in parentheses denotes Cronbach's alpha calculated from our data because the sources referred to did not provide this information.

2.4. Analyses

Whether the training program longitudinally impacted digital competences and attitudes, paired mean comparisons (*t*-tests) with effect sizes (Cohen's *d*) were utilized for pre–post measurements. The assumptions for a paired *t*-test include the analyzed variable to show homogeneity of variance and normal distribution. However, these assumptions have been relativized in studies of the robustness of the *t*-test [44–46]. Since several of the considered variables did not meet these assumptions, the *t*-test results were double checked using appropriate methods. In case of assumption violation, Wilcoxon sign-rank tests were conducted. Since the results remained consistent, they are presented in a uniform *t*-test table for a better overview. The analyses were performed with SPSS v28.0.1.1 (14), and one-sided *p*-values are used as the hypotheses are directed.

Given that 15 dependent *t*-tests were conducted, the likelihood of a Type I error (false rejection of the null hypothesis) increases. To account for the risk of inflated false significant results due to multiple analyses addressing the same research question, it is important to consider that some significant results may be due to chance. Therefore, the Bonferroni correction method is applied, which adjusts the significance level to $\alpha = 0.003$ to control for the risk of Type I errors. A priori power analysis conducted with G*Power v3.1.9.7 suggests a sample size of at least $n = 55$ to achieve sufficient power (>0.80) and minimize the risk of Type II errors (false retention of the null hypothesis) for the following parameters: expected effect size ($d = 0.5$), Bonferroni-corrected α -level, and desired sufficient power. Since the sample size of participants who completed the program ($n = 40$) is 27.27% smaller than the suggested sample size of 55, post hoc power analyses were conducted to assess the power of the effects.

As it was not anticipated that the completion rate was going to lack the suggested statistical power for inferential statistics, some interviews were conducted post hoc to shed light on the causes of low completion rates.

3. Results

Table 3 illustrates that participants showed overall conducive attitudes and competence beliefs, except for lower TCK and a moderate cost perception at the very beginning of the training program. Knowledge domains range between 44 and 66% average correct answers. In detail, participants showed the most potential for improvement in Media

Literacy Education (44% average right answers) and Media Didactics Knowledge (47%). Still, the TPK Situational Knowledge (66%), TPK Conceptual Knowledge (61%), and Technical Knowledge (58%) also show potential for development. Considering the hierarchical structure of the TPACK model, it is unexpected that the percentage of correct responses in the most elementary TK domain is substantially lower than those in higher-order TPK and TPACK. Analysis of attitude measures revealed a differentiated pattern. Participants rated the implementation of digital technology in teaching practices to be more important and interesting than useful and rather costly regarding personal resources, while they also reported being incentivized to use digital technology for instrumental rather than hedonistic purposes. Therefore, it can be inferred that the participants are both extrinsically and intrinsically motivated to engage in learning about teaching with technology, have a robust yet expandable concept of the usefulness of it, and worry about the effort that is required for it.

Table 3. Mean comparison results between pre and post ($n = 40$).

Subscale	Pre		Post		$t(39)$	p	d
	M	SD	M	SD			
TK	3.41	0.91	3.61	0.74	1.999	0.026	0.316
TPK	4.06	0.58	4.03	0.47	−0.322	0.374	−0.051
TCK	2.71	0.95	3.29	0.76	4.016	0.000	0.635
TPACK	3.91	0.62	4.00	0.59	0.813	0.211	0.129
Technical Knowledge	15.15	4.16	16.50	4.77	2.396	0.011	0.379
Media Literacy	7.45	1.87	6.85	2.34	−1.578	0.061	−0.249
Education	10.35	3.22	10.16	4.02	−3.399	0.346	−0.063
Media Didactics	63.83	7.97	63.25	8.35	−0.509	0.307	−0.081
Situational Knowledge	19.60	2.94	18.88	3.68	−1.258	0.108	−0.199
Conceptual Knowledge	4.02	0.75	4.05	0.74	0.243	0.405	0.038
Usefulness	4.31	0.69	4.38	0.79	0.545	0.295	0.086
Interest	4.43	0.60	4.38	0.83	−0.310	0.379	−0.049
Importance	3.43	0.78	3.56	0.85	1.213	0.116	0.192
Cost	3.49	0.39	3.46	0.45	−0.310	0.347	−0.063
Instrumental Use	2.18	0.74	2.25	0.65	0.545	0.267	0.099
Incentive							
Hedonistic Use							
Incentive							

p -values are reported as being one sided.

3.1. Effects of the Program

TK competence beliefs and Technical Knowledge differences are statistically significant below the standard α -level of $p = 0.05$ and show small effect sizes ($d < 0.5$). TCK competence beliefs are the only differences that are statistically significant below the Bonferroni corrected α -level of 0.003 and show a moderate effect size ($d > 0.5$). No other differences show statistical significance. In other words, the null hypotheses for improvements due to the training program must be largely retained, except for TCK competence beliefs.

Given the low completion rate and limited effects, it seems plausible that, next to difficult project and pandemic circumstances, the quality of the program has been influential as well. The interviews on the participants' experience of the program's SQD strategy integration give insight into critical criteria.

3.2. Post-Interview Feedback

The interviews suggest that perceptions were largely congruent among completers and non-completers. Selected statements, sorted by their relevance to SQD strategies, are depicted in Table 4. They mainly reflect limitations. For the alignment of theory and practice, participants felt that theoretical tasks were not reinforced with practical

application, limiting their effectiveness. Role modeling was perceived to be largely confined to pre-recorded videos, which were not perceived as inspiring. Reflection activities, such as self-study and portfolio tasks, were present but lacked integration with real-world contexts. Instructional design was perceived as overly theory laden, with participants noting an absence of practical application. For collaboration with peers, the use of the online forums was limited by a rather self-representational than dialectic use. Authentic experiences were perceived as limited, with participants expressing a general need for hands-on practice directly relevant to classroom scenarios. The quizzes after each section to provide feedback were initially perceived as fun but ultimately led to frustration due to technical difficulties concerning the interpretation of correct text inputs.

Table 4. Selected interview statements about SQD strategy integration.

SQD Strategy	Interview Statements
Aligning theory and practice	RC: “[...] I think it’s something completely different if you just read through it and work on the tasks. But if you actually put it into practice, that’s a completely different thing. And I think that could help.”
Role models	RC: “It was just there with those teaching videos, that one, of course you can kind of see that as role models, but otherwise I would say it was rather neglected.”
Reflection	RC: “We always had these self-study tasks in between and there were also these reflection tasks in between, where you were simply given a task to think about something specific or to repeat what you had learned. And I would say that the portfolio tasks also covered reflection quite well.”
Instructional design	RC: “I would say that the learning opportunities were definitely there and also useful, but in order to consolidate the whole thing, perhaps more tasks or practical components would have been useful.”
Collaboration with peers	RC: “There were often these forum pages in between. [...] you could simply see what the others thought about the topic and what the others had solved.”
Authentic experiences	RNC: “There was nothing that I would say now that I have really applied something that I can do in the same way later. [...] It was more of a basic knowledge transfer.” RNC: “[They] definitely tried to implement it. Always by means of these mini quizzes behind a section, where you were only ever asked brief questions about what was part of it. I took part in it at the beginning and actually thought it was very cool, but then it turned out that if you did it on your own, there was a lot of free text and I found that difficult, because it sometimes didn’t take answers that you had formulated yourself, even though they were actually correct, just because they were worded differently. [...] So that was actually one of the big reasons why I dropped out at some point because it just wasn’t fun.”
Feedback	

RC = response of completer; RNC = response of non-completer.

In addition to the limitations in the implementation of SQD strategies, the interviewees addressed an underestimation of knowledge levels, a lack of incentives, a lack of human interaction, and more technical difficulties as relevant themes contributing to their experience of limitations in the program. First, as the NC interviewee put it, “When I think about what I know now, it’s probably more the basic skills that I can use for all the digital things. So, I think I can already use them, but I think there’s a lot more to learn and I was kind of hoping for that” Thus, the interviewee seems disappointed in the simplicity of the content, indicating that their competence level was above the anticipated entry level from the start, limiting their engagement with the material.

Another significant theme was the value of extrinsic incentives, particularly in relation to the program’s assessment approach. Participants noted that some form of evaluation could positively impact their engagement and effort. As one interviewee suggested, “I do believe that there should be something in between where you at least have the feeling that it’s being checked in some way and has an influence on whether I end up with this certificate or not. It probably makes sense, because then you just deal with things differently and don’t just click through”.

The lack of human interaction in the online program format was another concern. Participants felt that increased personal connection would enhance their commitment and engagement. One participant shared, “If you do it as a purely online self-study course,

then I think it might be better to establish a bit more contact, because then it's not so anonymous". Another participant emphasized this sentiment, explaining, "You didn't feel that kind of personal connection [...] that you develop a kind of guilty conscience if you don't do it. It is just something else if there is a person behind it".

Moreover, technical difficulties were a recurrent issue, impacting the user experience in several domains. The RC explained concerning the representation of information, "what is sometimes difficult is that, depending on which browser you use, some content is not displayed. So, videos are not displayed, or images are not displayed", the input of information, "[...] with the self-study tasks there were sometimes problems with not being able to send anything". Similarly, the RNC response to the SQD strategy of feedback highlights more severe aspects of input difficulties (see Table 4). Participants also objected to the user friendliness of the portfolio when saying, "using the portfolio is rather complicated. I would have liked an introduction to this".

On the other hand, the interviewees also highlighted several strengths of the program, particularly appreciating aspects of the portfolio instructions, the online format, and the content width. As one interviewee noted, "The portfolio tasks in any case, because they were often creative tasks. I liked that because you weren't so restricted in what you could do because you were left to work it out yourself".

Another strength participants identified was the independence of time and place offered by the self-study format. One interviewee expressed appreciation for this flexibility, stating "I have to say that I also liked the fact that you could do it at any time and from any place, so it was purely self-study, because you could do it when it suited you". This structure enabled participants to engage with the program at their own pace, accommodating personal schedules and preferences.

Additionally, participants viewed the DigCompEdu-oriented content themes as well chosen and relevant to the teaching profession. They appreciated that the program covered practical and essential topics. One interviewee remarked, "I thought the topics were good because they actually covered many relevant aspects of school. So, everything that you have to think about in advance at school or even when you're at school. [...] Also, the legal things, for example. But I also think that you got suggestions for tools that you can use".

4. Discussion

Given the overall heterogeneous state of research, meta-studies on the integration of digital technologies into teaching practices have revealed some relevant features [34,35]. Reported effects rise if the subjects are pre-service teachers compared to in-service teachers, if randomized experimental designs are applied (in contrast to quasi-experimental), if there is a longer-lasting intervention duration (up to three months categorized as short, to six months as medium and over six months as long), if they are evaluated by means of standardized tests, if there is a theoretical knowledge focus, if there are method- and tool-based approaches, and if there is a mixed, online and offline, teaching environment [35]. Features of our study (aiming at pre-service teachers, pre-experimental design, long program timeframe, use of standardized test instruments, focus on theoretical aspects due to an online teaching environment, and some tool-based approaches) only partly overlap with the above-mentioned study features, which are adequate to induce prominent effects.

The evaluation of the program's impact on participants' digital competences and attitudes reveals soberingly that pre-post differences in dependent variables remain statistically insignificant on the Bonferroni method-corrected α -level, except for the difference in TCK, i.e., the understanding of how technology and subject content influence each other. Accounting for the small sample size, post hoc power analyses show a strong power for the effect sizes in TCK competence beliefs (>0.80). Ergo, the effect is robust. This is particularly surprising because TCK is the only domain within the TPACK model that was not explicitly addressed in the program. Even though it seemed plausible that working on their technological teaching skills within the program would impact their TCK, because participants would inevitably link them to content specific to their teaching domains, the

absence of effects in other measures and the interview statements addressing the lack of practical aspects indicate that the potential for any transmission was rather small. Thus, it cannot be ruled out that the TCK effect was not attributable to the program's contents but to the simultaneous course of study in their subjects, in which the technological enrichment of professional methods is probably more natural to teach. A facilitating condition for this result was that TCK, in comparison to the other competence beliefs, was rated rather low. Therefore, there was comparably more potential for development. For future programs or curricular implementation, this indicates that there is probably less need to address TCK. Thus, tasks could presuppose TCK, especially in later semesters.

Despite participants demonstrating strong TPK competence beliefs, their TK competence beliefs were substantially lower. Considering the hierarchical nature of the TPACK model, where TK forms the foundation of higher-order knowledge domains, such as TPK, this result is unexpected. A possible explanation could be a confounding effect with PK competence beliefs, as participants—probably based on their prior experiences leading to a teaching career plan—show strong PK competence beliefs. This may have inflated their TPK competence. The data—even though they were not planned to be used for this contribution, as PK was still measured for other purposes—support this hypothesis, as competence beliefs in PK were the highest among all TPACK domains ($M = 4.13$, $SD = 0.53$), indicating that their beliefs concerning pedagogical knowledge may be inflating their TPK competence beliefs.

For future programs or curricular implementations, this could be considered as a call for TPK challenges to test their beliefs and adjust them if necessary. Additional support for this is found in interviewee statements that reflect the hope to be more challenged, e.g., “if I think about what I know now, then it's probably more the basic skills that I can use for all the digital things. So, I think I can already use them, but I think there's a lot more to learn and I was kind of hoping for that”.

The statistically significant differences in TK competence beliefs and Technical Knowledge on a $p < 0.05$ α -level are noteworthy, even though they do not meet the Bonferroni-corrected threshold. While it is possible that some significant results may be false positives, the fact that both measures align provides some support for the conclusion that the program improved technical expertise. Post hoc power analyses also support this interpretation with moderate power (>0.40) at the standard α -level. As a major limitation of the program is the lack of practical application and no statistical effects on TPK competence beliefs and knowledge, this could mean that TK competence beliefs and knowledge are more malleable for programs with a theoretical focus than TPK. Therefore, future programs or curricular implementations could have a self-study program with a theoretical focus for TK as a pre-course for TPK development courses with a rather practical focus and guided learning.

Although participants entered the program with comparatively favorable baseline attitudes toward digital media use in education—viewing it as important and interesting—the program did not lead to notable improvements in these dispositions. Given their already favorable attitudes, there may have been limited room for further positive change. However, it was still expected that the perceived costs associated with using technology in teaching would decrease and the perceived usefulness would increase through program participation. The lack of observed change in these areas likely stems from the program's limited focus on practical, hands-on applications, which could have reinforced the perceived value and ease of integrating digital tools. For future programs aiming to impact attitudes meaningfully, integrating more authentic instructional exercises may allow participants to experience technology's potential to enhance learning while addressing common barriers to adoption.

Since there were no statistical effects on TPK and TPACK competence beliefs and corresponding knowledge, despite participants having shown a conducive attitudinal foundation from the start and even being the focus of the program, it seems that the program did not fulfill its central aspiration—to improve the competence of pre-service teachers

to integrate digital technologies into their teaching practices regularly and effectively. In conclusion, those parts of the training program cannot be recommended to be adopted by future programs or for curricular implementation based on the current data. However, the low post hoc power (<0.40) of these insignificant test results means that due to a small sample size, there is a higher risk for them to be rather random than true. Therefore, these results need to be interpreted with caution to inform recommendations for future programs and curricular implementation. The extensive limitations of this study also shed light on practical implications for similar programs and curricular implementation.

4.1. Limitations and Practical Implications

4.1.1. Pandemic Circumstance and Social Interaction

The training program was designed as an online self-study course, primarily due to pandemic-related restrictions and project-specific limitations. The pandemic deprived university students of possibilities to fulfill basic needs that were vital to their emotional well being, which especially impacted pre-service teachers in comparison [47]. Thus, possible effects on the completion cannot be ruled out. It seems plausible that pre-service teachers in full lockdown registered partly from a perspective of social isolation and emotional ill being and were motivated by boredom and the desire to do something meaningful for their careers. When restrictions were successively lifted and essential means to connect to their peers in person became more available, the interest in and importance of working on the training program probably declined in comparison. Some pre-service teachers only registered because of the pandemic, while others would have registered and completed the program regardless, if not for the opportunities created by the end of pandemic restrictions. This suggests that without the pandemic, fewer might have registered, but more would likely have finished the program. For comparison, there were studies with vaguely similar online training programs for pre-service teachers to integrate digital technology into teaching practices effectively that took place before the COVID-19 pandemic and showed limited effects. These studies emphasize difficulties in implementing practical technology use within pedagogical strategies in online scenarios and a lack of authentic classroom experiences as major limitations for effects. Thus, they highlight structured guidance for TPK strategies and hands-on, practical experiences that are contextualized in a holistic teaching unit rather than just parts of it [48–50].

In retrospect, one could have considered the pandemic circumstances not just as something to merely adapt to in an online format but also something to counter its effects, like emotional ill being, which would probably have also supported a larger sample size. Especially, to counter social disconnection, an emphasis on a sense of community, peer collaboration, and mentoring in advertisements and contents should facilitate registrations and prevent dropouts. Thus, one could illustrate successful and engaged online collaboration practices in advertisements and implement tasks that require synchronous collaboration, such as group projects in break-out sessions.

4.1.2. Online Format and SQD Strategy Implementation

Apart from the pandemic, one reason to carry out the training program as a self-study online course was the fact that the training program was embedded into a project of limited duration. Consequently, the project structure did not allow for sustainable personal resources. Thus, it was not possible in the long term to provide face-to-face interaction between students and teachers. This might have been a significant constraint in the design of the training program, as a human factor was missing. Accordingly, the decision to carry out the training program online also had a decisive impact on the integration of the SQD strategies and led to the difficulty in integrating all the strategies from the SQD model. Specifically, the lack of authentic teaching experiences with technology and real-time role model observation are critical deficiencies, which are also reflected in the interview data.

Regarding authentic experiences, students felt the alignment of theory and practice was limited and demanded more hands-on practices. Consequently, the lack of authentic

experiences could have reduced students' engagement and self-efficacy experiences. When students have few opportunities to apply their knowledge directly and to apply what they have learned in real-world scenarios or solve real problems, they may develop less confidence in their ability to tackle real-life professional challenges. Accordingly, students did not have the opportunity to apply their professional knowledge "in action". Authentic experiences, such as implementing digital media, often provide immediate feedback, helping students to assess their progress and reflect on their competences. Without these practical application contexts, feedback may remain abstract, potentially hindering the development of competences.

Limited alignment of theory and practice might have also resulted in students not seeing the relevance of theoretical knowledge to practical contexts. This disconnect can lead to frustration and lower motivation and engagement, as the material provided may feel less applicable. To address these limitations, future training programs need to include more practical components, such as real-world classroom scenarios, to build challenging experiences. Interestingly, the results of this study show a gap between perceived competence beliefs and actual knowledge. Integrating more practical phases could recalibrate these competence beliefs, as practical scenarios could illustrate the complexity of technology integration and clarify the need for further competence development. Online formats of such training programs could, e.g., use video conferencing tools to carry out digitally mediated learning scenarios in the form of microteaching. Students could simulate the role of a teacher and of a student to solidify their learning through hands-on practice.

With regards to the SQD strategy of role models, students felt that the videotaped lessons provided were not inspiring—however, these are especially crucial for motivation and identification. The training program might have missed in-person live interaction to give students more concrete ideas on how to apply the content in practice and develop certain attitudes and competences. Observing inspiring role models handle real-world situations could lead to the development of professional values and foster motivation to use technology. Moreover, observing role models could also encourage interaction among peers by fostering discussions and exchanges to reflect upon certain practices. Adding to the limitations on lacking practical, authentic, and holistic aspects of teaching with technology, limited access to role models probably impacted attitudinal developments as well since their premise would probably have been a deeper fascination for and understanding of digital technologies' usefulness, importance, and cost for teaching. Therefore, future training programs should focus on more critical SQD strategies of authentic experiences and role models as best as possible, especially for the development of positive attitudes and TPACK dimensions beyond TK. As a solution for online formats, training programs could include case studies or simulations where experts demonstrate the application of newer technology that students might perceive as innovative and inspiring. Moreover, it would also be conceivable to include video interviews, presentations, or live Q&A sessions with experienced professionals to offer examples of practical application and exchange previous experiences. In this respect, it is of utmost importance to train teacher educators in the professional application of technology to act as "best-practice" role models and experts.

Lastly, as a human factor was missing in the form of a face-to-face interaction with a teacher, no guidance or individual feedback on the reflection activities could have been provided. However, reflection is especially fruitful when paired with formative feedback [29,30]. Consequently, reflection phases should also be accompanied by structured feedback that could be taken over by AI applications in case human resources are not available.

4.1.3. Underestimation of Knowledge Levels and Bottom-Up Content Development

Given that registered pre-service teachers showed statistically significantly more prior knowledge than other pre-service teachers [40] and the RNC interview indicated an underestimation of knowledge by design, the circumstance that participants had to work through potentially known information on their entry has led to frustration and

disappointment that probably had a detrimental impact on the progression beyond their prior knowledge.

Internal differentiation could facilitate adequate difficulty levels to avoid disengagement. For example, a dynamic program workflow, where participants begin at different entry points based on their pre-measurement knowledge test results, could be an effective measure.

Building on their already positive attitudes, pre-surveys could, furthermore, help to tailor programs according to the expectations of participants. Advertising a program that is aligned with their interests should be more effective in general but also could serve as a guide for bottom-up content creation, potentially facilitating sustainable engagement and improving completion rates. Furthermore, one could limit the participation capacities to turn them into a privilege for greater attractiveness. This would also entail plannable resources to supervise participants and provide more human interaction since the workload would become calculable.

4.1.4. Technical Difficulties and Extensive Pre-Testing

Technical issues were mentioned particularly frequently in relation to the e-portfolio, which suggests a need for additional guidance on navigating and using the platform to reduce frustration and improve the learning experience.

Some of the technical difficulties reflected in the interviews come as a surprise because technical feedback options were provided after each module and technical assistance was available but not claimed, especially considering their magnitude concerning disengaging behavior, e.g., as depicted in the response to feedback in Table 4. Therefore, it seems that the threshold to claim assistance or provide feedback was too high.

To prevent such pitfalls, first, it is advisable to prevent technical difficulties in the first place. Since the choice of LMS was led by resource efficiency rather than actual effectiveness, one should have anticipated the functionalities needed to find the most fitting LMS for the purpose and not bargain, especially on crucial features, such as formative feedback. Additionally, there should be more extensive pre-tests or even a pilot study to identify and repair dysfunctions beforehand—especially concerning basic features, such as the display of media elements in the browser. Second, lower threshold solutions when a technical issue has occurred could incorporate an FAQ resource or regular check ins where students can ask questions and receive feedback on their technical issues.

4.1.5. Shortcomings in Instrumentation and the Need for Better Instruments

The circumstance that the knowledge test items do not completely align with the contents of the program in width and depth could account for some lack of statistical effects. The width aspect regards the difference between what DigCompEdu knowledge was taught in the program vs. what TPK and Media Pedagogy knowledge was tested. Hence, despite the great overlap between them, it still poses a potential source of distortion, especially since some knowledge, e.g., legal aspects of digital teaching, was not reflected in the tests and vice versa for some aspects that were assumed to be related enough for effective extrapolation from what was taught.

A potential misalignment in depth is based on the differentiation in levels of learning. In other words, the type of knowledge required to solve a task might be different between instruments and, thus, some might align worse with what has been taught. According to the revised version of Bloom's taxonomy, there are four types of knowledge that build on each other: Factual Knowledge as granulated pieces of knowledge, Conceptual Knowledge as the connections between those elements, Procedural Knowledge as a methodological perspective for the elements and their connections, and Metacognitive Knowledge as a strategic perspective on how to acquire the types of knowledge [51]. These types of knowledge enable one to solve different levels of tasks (to remember, to understand, to apply, to analyze, to evaluate, and to create) [51].

Now, taking another look at the example items of the instruments for Media Pedagogy Knowledge and TPK Knowledge, the items for the Technical Knowledge subscale differ from the others in the type of knowledge required to solve them. While the others rather require understanding, i.e., Conceptual Knowledge, to answer correctly, Technical Knowledge requires remembering, i.e., Factual Knowledge. This is consistent with other items of the tests. Therefore, the pre–post-test differences are rather significant for the instruments that required Factual Knowledge but not for the instruments that required higher-order knowledge. In conclusion, the assumption that the difference between what knowledge was taught vs. what knowledge was tested in width and depth would be bridged on its own could not hold.

Aligning the content of the program with knowledge tests—both in terms of the width and depth of knowledge—would allow for more reliable assessments of test knowledge effects and, if used for internal differentiation, also for a more tailored learning experience. Hence, for the evaluation of DigCompEdu competences, respective instruments that are suitable for scientific evaluation are needed. A recent example of competence beliefs was published in 2023 [52]. A respective knowledge test should be developed in future research. Ideally, DigCompEdu performance tests would also be researched and implemented additionally for a more holistic measurement of competence.

4.1.6. Dropout Rate and the Need for Better Marketing

Ensuring a completion rate to provide robust statistical power is essential to prevent the uncertainties about statistical effects in this study, which are indicated by the post hoc power tests. Based on the registrations and due to a lack of empirical evidence concerning the completion rate of extracurricular programs in higher education, the completion rate was intuitively expected to result in a more than sufficiently large sample size to carry out the analyses. Retrospectively, considering broader literature research, an estimation could possibly have been made based on related findings, such as for Massive Open Online Courses (MOOCs), in which a median completion rate of 12.6% was reported for over 200 courses [53].

A variety of features could have prevented the high rate of non-completers. In general, future programs could coordinate cooperations with other universities to expand the participant acquisition radius. Beyond mere quantity, motivational measures could also support the quality of participation. Thus, incentives that motivate participants to follow through (e.g., obtaining certificates that are visibly valued in the labor market) should be planned diligently. Accreditation that enhances career prospects should be a priority. Then, based on the RC interviewee, more challenging tasks that are critical for success could prove additionally effective. Similarly, more human interaction, e.g., for guidance and structure, could also prove effective. For example, setting time limits for module completion or sending reminders to inactive participants could assist in maintaining momentum and engagement by facilitating “a guilty conscience”, as an interviewee put it.

4.2. Conclusions and Lessons Learned

This evaluation of a pre-experimental DigCompEdu competence training program for pre-service teachers was conducted during the COVID-19 pandemic. The program considered the importance of SQD strategies but was constrained by limited project parameters and pandemic circumstances, particularly in practical and authentic experiences, role modeling, and collaborative learning. Thus, it emphasized theoretical knowledge with limited tool-based approaches and was delivered in an entirely online, self-directed format with technical difficulties. The assessment utilized standardized instruments to measure technical pedagogical competences but not DigCompEdu-tailored test instruments, and it faced challenges due to a small sample size.

The generalizability of these findings is thus restricted, and the lack of observed indicators for developmental differences additionally restrict the direct deduction of facilitating conditions. Nevertheless, valuable insights for future programs, curricular implementation,

and further research have emerged in post hoc analyses, and the discussion of the results and limitations is as follows:

- Provide role models that demonstrate difficulties and solutions in practical challenges to inspire curiosity and ambition amongst participants concerning the usefulness and ease of use of digital technology for teaching.
- Include practical application of theoretical elements for TK aspects in general, but particularly for TPK aspects, to concretize potential difficulties and potentials.
- Determine knowledge levels beforehand and take advantage of conducive attitudes and competence beliefs by pre-testing and providing substantial yet manageable practical challenges to calibrate inflated competence beliefs.
- Provide scaffolding measures, peer learning, regular reflection, and formative feedback opportunities to facilitate the development of in-depth knowledge.
- Monitor and build on parallel TCK development to facilitate TPACK on top of TPK.
- Ensure sufficient TK premises to advance into TPK but do not presuppose insufficient TK to avoid over- and underchallenging conditions.
- Generate and consider bottom-up input in content creation and incentive structures for a tailored experience to facilitate continuous engagement and perseverance.
- Invest in a pilot study or extensive pre-testing and regularly request feedback on the LMS to identify and resolve technical difficulties before detrimental impacts.
- Utilize proven marketing strategies (e.g., limited supply and time limits) and seek partnerships with other teacher education institutions to acquire and sustain larger sample sizes and improve program visibility.
- Sacrifice comparability for better alignment between taught content and tested knowledge by tailoring existing knowledge measures to your needs or developing new ones that reflect DigCompEdu competences to reduce uncertainty in the assessment results and ensure more reliable evaluations of program impact.

The aim of this study was to contribute empirical evidence to inform future training programs and curricular implementation to encourage and enable pre-service teachers to integrate digital technology effectively into their future teaching practices. Even though the program lacked anticipated effectiveness, future implementations can still benefit from the lessons learned outlined in this paper.

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Article

Self-Control or Crime Control: Teachers' Insights on Good Practices in 1:1 Classrooms and Implications for Professional Development

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Abstract: Norway ranks high in digitalization in schools, with over 90% of students in grades 1–10 having their own digital device supplied by their school districts and reporting the highest use of digital tools globally in the latest PISA report. However, research shows that implementation processes and competence measures for teachers' professional use of digital devices vary considerably between schools. This study aims to inform the development of research-practice partnership (RPP) measures focused on professional digital competence development in digitalizing schools internationally by exploring what teachers consider important for good teaching practices in 1:1 computing classrooms. We draw on both closed and open survey responses from 1505 Norwegian teachers in highly digitalized schools where the most experienced teachers have had 1:1 computing since 2014. The findings show that classroom management is seen as gradually more important with higher digital teaching competence and more experience, but that the teachers' understandings of what digital competence entails and their use of classroom management strategies are rather limited. The study concludes that professional competence development measures that provide broader understandings of digital competence and classroom management are needed, dependent on competence levels and experience, as well as systematic training of students' digital self-regulation.

Keywords: professional digital competence development; in-service teacher education; digitalization; classroom management; research-practice partnerships

1. Introduction

Society and schools are becoming increasingly digitalized, with digital tools shaping our behaviors, work, and learning processes [1]. This digital transformation is regarded as one of the greatest challenges that today's teachers must navigate [2]. Internationally, Norway ranks high in school digitalization, with over 90% of primary and secondary students equipped with personal digital devices provided by their school districts, a model referred to as 1:1 computing [3,4]. According to the latest PISA report, Norwegian students also utilize digital tools more than their peers in any other country [5]. As a result, Norwegian teachers must consider the impact of digitalization not only on facilitating academic learning across various subjects but also on promoting social-emotional learning and fostering student digital self-regulation.

Despite this, Norwegian teachers report varying levels of professional digital competence (PDC) [3,6]. PDC has historically developed as a concept in tandem with increasing digitalization in schools internationally, evolving from generic and instrumental digital competence understandings towards didactic skills and digital teaching competence in specific school contexts [7], and further to include both specific ethical, agentic, and societal perspectives [3,8]. In recent Norwegian research, PDC encompasses a specific set of digital

skills, knowledge, and abilities pertinent to the teaching profession, including technical, pedagogical, ethical, relational, agentic, and societal perspectives [3,7,8]. Furthermore, studies indicate that in-service teachers in Norway, as well as internationally, do not feel adequately prepared to teach in technology-rich environments [9,10] and express a need for professional development in this area [11]. Additionally, the support teachers receive through further education to develop their PDC varies significantly between schools, both in Norway [3] and in other countries undergoing digitalization [12].

To support schools in their continuous professional development efforts and enhance in-service teachers' competencies, research-practice partnerships (RPPs) between schools and teacher education programs have significantly increased in Norway and elsewhere over the past two decades [13,14]. However, research on the development of PDC in Norway has often emphasized instrumental aspects, such as technical proficiency [8,15]. In contrast, a study examining the 1:1 implementation process in Norwegian schools from 2017 to 2019 highlighted the importance of changes in teaching practices and classroom management strategies as teachers gained experience with 1:1 computing [16]. Similarly, a smaller-scale study from 2019 found that Norwegian teachers reported the necessity for more explicit classroom management when using digital devices [17].

Consequently, our study aims to provide a broader and more nuanced understanding of what teachers in highly digitalized schools consider essential for teaching in 1:1 classrooms. We analyze survey responses, including both closed and open-ended questions, from 1505 Norwegian teachers in schools engaged in RPP efforts, where the most experienced teachers have been utilizing 1:1 computing since 2014. This paper seeks to contribute to the development of future RPPs by addressing the following research question:

What aspects do teachers emphasize for good teaching practices in 1:1 computing classrooms, considering their self-perceived digital teaching competence and experience with 1:1 computing, and what challenges do these aspects present for professional development measures in research-practice partnerships?

Through this specific focus, we aim to contribute to how other countries implement professional development within their school digitalization processes. We will first review international and national research on 1:1 classrooms along with the empirically relevant theoretical frameworks associated with this body of work before providing a detailed methodological overview of our study.

1.1. Previous Research on 1:1 Classrooms

Numerous international studies have shown that 1:1 computing can significantly improve student academic performance across various grade levels and subjects [18,19]. The literature further emphasizes that 1:1 solutions enhance student communication and collaboration [19,20], as well as increase student motivation and school attendance [21,22]. However, a key finding from a recent meta-review indicates that these positive outcomes depend heavily on teachers' decisions, including which devices and tools are used, the intended purposes of their use, and the pedagogical strategies applied [3].

Other studies emphasize that teachers face challenges that must be addressed before they can effectively use digital tools and facilitate high-quality, student-centered learning processes. These challenges may stem from what Ertmer [23] refers to as first-order barriers to innovative practice, such as inadequate access to or malfunctioning technological infrastructure, hardware, and software [24], or, as previously noted, teachers' competence and need for professional development. Additionally, challenges may involve second-order barriers [23], including school culture, institutional support [25], teachers' beliefs—specifically their epistemic views on teaching and learning and perceptions of the value of technology in the classroom [26,27].

Studies from 1:1 classrooms in Norway also highlight these challenges. While many teachers report using digital tools to facilitate active, collaborative, and creative learning processes [3], earlier research on students' experiences with 1:1 computing indicates that much of their work remained individual, focusing on traditional tasks like text produc-

tion, information retrieval, and presentation preparation [17]. A large-scale classroom observation study from 2014 to 2015 in grades 8–9 supports these findings, showing that teachers primarily used computers for instructional presentations, while students mostly used word processors for writing [28]. Additional research suggests that the early phase of 1:1 computing, where digital devices are used for tasks similar to those previously carried out with analog tools, continues to dominate in many classrooms [29,30].

More recent studies offer a more nuanced view of 1:1 computing in Norwegian schools. While traditional tasks such as using word processors and presentation software still prevail, there is a growing trend of students engaging with digital tools for more creative and interactive learning experiences. Researchers have observed lessons where digital tools greatly enhanced learning, but they have also reported instances where the tools were underutilized or misused, reflecting disparities in teachers' digital competence and pedagogical practices [29,31,32]. Classroom management is a key factor in this variability. A survey of 338 teachers identified classroom management as the most critical skill in technology-rich environments, with over half emphasizing the need for stricter control in digital classrooms. Nearly 90% agreed that clearer rules are required in 1:1 classrooms compared to traditional settings [17]. Tømte et al. [33] further supported this finding, noting that during the initial phase of 1:1 implementation, teachers struggled to manage distractions, such as students browsing the internet or watching YouTube during lessons. In response, schools implemented stricter rules and blocked certain websites to regain control. While these measures alleviated some issues, they also frustrated both students and teachers, limiting opportunities for creative and flexible use of digital tools and hindering the development of students' digital responsibility and self-regulation [33].

Research from Norway's upper secondary schools, where 1:1 computing has been implemented since 2007–2008, similarly highlights the critical role of classroom management. Moltudal et al. [34], using data from a national mixed-methods study in 2013, investigated the relationship between teachers' self-reported digital competence and their classroom management strategies. They identified four key components essential for effective management in 1:1 settings: *Teacher-Student Relationships*, which are crucial for minimizing disruptions and promoting positive engagement with digital tools; *Control and Structure*, particularly important for teachers with lower digital competence who depend on clear rules and consistent enforcement; *Managing Non-Academic ICT Use*, which requires clear expectations and monitoring to prevent distractions, such as social media; and *Adaptation and Flexibility*, where teachers with higher digital competence are better able to integrate technology, adapt strategies, and maintain order to foster learning.

Although classroom management strategies may have evolved since the 2013 data collection and could differ across lower grade levels where students are less independent, initial analysis in our exploratory study of 1505 teachers from grades 1 to 10 revealed that experienced teachers still view classroom management as the most important aspect of teaching in technology-rich environments. Thus, a conceptual understanding of classroom management is central to this article and needs to be defined and clarified. In the following section, we give a brief overview of some of the main concept facets that are relevant for comparison with Moltudal et al.'s [34] previous study and for our final reflexive thematic analysis and discussion of teacher perceptions.

1.2. Conceptual Understanding of Classroom Management

Classroom management is broadly defined as “the actions teachers take to create an environment that supports and facilitates both academic and social-emotional learning” [35] (p. 4). Similarly, Doyle [36] outlines two key objectives for classroom management: the first is to establish a quiet and orderly environment conducive to meaningful learning, and the second is to promote students' social and moral development, fostering both academic and personal growth, as also emphasized by Evertson and Weinstein [35]. Both definitions underscore the central role of teacher actions in facilitating student learning.

Classroom management involves a variety of practices and strategies that teachers can use to create an optimal learning environment [37]. A meta-analysis by Korpershoek et al. [38] identified five essential practices for effective classroom management: (1) building caring and supportive relationships with and among students; (2) organizing and delivering instruction to maximize students' learning opportunities; (3) fostering student engagement through group management techniques, such as establishing rules and procedures; (4) promoting students' social skills and self-regulation, encouraging responsibility for their behavior; and (5) applying appropriate interventions for students with behavioral challenges.

Wubbels [39] categorizes classroom management strategies into those that promote internal or self-regulation and those that regulate behavior externally. Internal regulation is more student-centered, focusing on developing self-discipline and self-control by teaching social-emotional skills, building supportive relationships, setting firm yet fair boundaries, and sharing responsibilities with students [39]. This approach fosters self-regulation through caring relationships and mutual respect, where teachers are warm, attentive, and supportive, yet also place expectations on students [35]. In contrast, external regulation follows a behaviorist approach, emphasizing the external control of student behavior through positive and negative reinforcement. This teacher-centered strategy relies on practices like praise, approval, punishment, and the clear establishment of rules and directives by the teacher [39]. External regulation is also linked to the view of teachers as enforcers of "crime control", where strict rules are set and infractions are detected and punished [40].

Classroom management strategies can be further classified into preventive and reactive approaches [38], which closely align with internal and external regulation. Preventive strategies, such as establishing rules and procedures and fostering positive teacher-student relationships [41,42], aim to minimize disruptions before they occur. Another example is teachers circulating throughout the classrooms, monitoring screens, and observing student activities. They employ a strategy for "withitness", which means gaining awareness of what goes on simultaneously in a classroom [43,44]. This approach serves as a preventive measure that balances internal and external regulation through the strategic use of teacher presence.

In contrast, reactive strategies involve disciplinary interventions, like issuing warnings or punishments, in response to misbehavior. Research shows that preventive strategies, particularly those that enhance students' self-regulation, are generally more effective than reactive measures. For example, negotiating classroom rules rather than imposing them is widely regarded as an effective preventive approach [45]. Despite this, teachers frequently rely on reactive strategies, such as punishing disruptive students [46,47], although the effectiveness of these practices remains questionable. Both preventive and reactive strategies are employed in classroom management, often in combination. Additionally, some actions may have both preventive and reactive dimensions, as we will explore further in the Results section.

2. Materials and Methods

2.1. Data Set and Overview of Exploratory Sequential Research Design

The data for this study was collected as part of a larger research project funded by the Norwegian Directorate for Education and Training. This project produced a report that included a scoping review on the state of digitalization in international educational research, a document analysis of the historical development of official policies and white papers in Norway, and a survey on teachers' perceptions of digitalization in public schools, covering grades 1–13 ($n = 2554$) [3,48].

This study utilizes data from the survey, analyzed through a qualitatively framed and empirically oriented exploratory research design in the sequence of qual–quan–QUAL [49]. The goal of the study is not to generalize findings but to explore thematic tendencies in teachers' own understandings qualitatively. The primary focus was thus on a specific open

qualitative question: What contributes to good teaching in a classroom where every student has their own digital device?

The analysis proceeded through three phases: (1) an initial inductive thematic analysis [50] of the qualitative responses, followed by (2) cross-referencing the identified themes with participants' self-reported scores on two quantitative measures: digital teaching competence and experience in 1:1 classrooms. The main findings from this analysis were then (3) examined in depth through a qualitative reflexive thematic analysis [51].

We will further elaborate on participant involvement and the three analytical phases in our exploratory design, as well as discuss the study's limitations and ethical considerations.

2.2. Participants and Data Collection

The participating schools were strategically selected from three geographical regions across Norway, where the research team had established RPPs between schools and teacher education programs [14]. This selection aimed to achieve two primary qualitative objectives. First, it sought to maximize variation in 1:1 implementation to gauge how teachers in different contexts perceive digitalization and existing collaborative measures for professional development. To this end, efforts were made to include teachers from both urban and rural municipalities, schools of varying sizes, and those employing different types of digital hardware (PC, Chromebook, and iPad) and platforms (Microsoft 365, Google Workspace for Education, and Showbie). Furthermore, the selection encompassed teachers with diverse local and regional support structures and experiences with digitalization [49]. The second objective of this strategic selection was to enhance participation in the survey, leveraging the existing knowledge of and trust in the researchers involved. Researcher visits to the regions during the survey period, from May to October 2022, contributed to a participation rate of 58% of the total selection.

The predominantly quantitative survey was developed by a team of four researchers and piloted in two iterations with ten teachers. Drawing on established survey instruments, it comprised 22 quantitative questions, primarily based on Likert scales, and three open-ended questions. All items were related to digitalization in schools, teaching methods, approaches to competence development, and leadership. For further details on the survey design, see Munthe et al. [3,48].

A total of 2554 teachers from grades 1 to 13 participated in the survey. However, participation from upper secondary schools (grades 11–13) was low ($n = 144$), leading to their exclusion from the analysis. Consequently, 2410 teachers from 149 schools in grades 1–10 were included in the study: 31% ($n = 737$) taught primarily in grades 1–3, 28% ($n = 683$) in grades 4–7, and 41% ($n = 990$) in grades 8–10.

For this study, we focus on one of the open-ended qualitative questions regarding “what contributes to good teaching in 1:1 classrooms”, along with two closed questions concerning digital teaching competence and experience in 1:1 settings. A total of 1505 teachers responded to the open-ended question, with 30% from grades 1 to 3, 29% from grades 4 to 7, and 41% from grades 8 to 10. Thus, grades 4–7 had slightly higher representation in the responses to the specific open-ended question than in the overall survey.

2.3. Analytical Phases

2.3.1. Phase 1: Initial Inductive Thematic Analysis

The first thematic analysis was conducted by a team of three researchers who performed initial double thematic coding using NVivo 14 to establish inter-rater reliability [49]. The codes were identified inductively from the data, and the researchers collaboratively synthesized the main themes from their individual coding efforts. This initial categorization of the 1505 responses led to the identification of thematic categories on aspects contributing to good teaching in 1:1 classrooms, with most responses encompassing codes from multiple themes:

- Classroom management (704 codings)
- Teaching practice (654 codings)

- *Resources, access or infrastructure* (425 codings)
- *Digital competence* (332 codings)
- *Digital competence development* (155 codings)
- *Motivation or Engagement* (113 codings)
- *Attitudes or beliefs* (90 codings)
- *Professional knowledge* (64 codings)
- *Policy* (13 codings)

The themes are presented in order of frequency, with *Classroom management* being the most frequently coded category (704 codings) and *Policy* being the least referenced theme (13 codings) in the informant responses. The first four themes are significantly more cited than the others; however, for further analysis, we also include the fifth most coded category, as it is relevant to the focus of this article: professional competence development.

2.3.2. Phase 2: Combining Qualitative Categories with Quantitative Measures

To further investigate the characteristics of competence and experience among teachers within the five most coded themes, as well as tendencies of potential development in their understanding of how to establish or maintain “good teaching” in 1:1 classrooms, we cross-referenced the qualitative themes descriptively with the self-reported scores of the 1505 teachers on the two quantitative measures A and B mentioned below. For clarity, we excluded responses from teachers who indicated “Before 2014” in the cross-referencing of themes with measure A, as we lacked information regarding when these teachers first began teaching in one-to-one classrooms. Since this study is qualitatively framed with a strategic informant selection, it was not our goal to find correlations or generalize from the findings but to look for descriptive thematic tendencies in this specific material.

As noted earlier, this study utilizes a selection of survey questions pertinent to our qualitative research focus, specifically the open-ended survey question: “What contributes to good teaching in a classroom where every student has their own digital device?” Additionally, we include two closed questions regarding experience with 1:1 computing (A) and self-perceived competence in teaching with digital resources, referred to as digital teaching competence (B):

- Year of introduction of 1:1 computing in their own classroom, measured with an interval scale ranging from ‘Before 2014’ to ‘Not yet’.
- “When I think about my use of digital resources in teaching, I see myself as a:”, measured with a five-point Likert scale from (1) Beginner to (5) Expert.

The more limited digital competence understanding in survey question (B) focuses solely on teachers’ teaching practices with digital resources. We will thus further refer to this as digital teaching competence, as we cannot know how the teachers themselves define PDC based on this question. We also chose to synthesize the five-point Likert scale in measure B to clarify three main groups of self-reported digital teaching competence. Teachers identifying as beginners (1) or inexperienced (2) were categorized as having “low” competence, while those in the middle category were classified as “medium” (3). Teachers who considered themselves experienced (4) or experts (5) were categorized as having “high” digital teaching competence. Among the total survey participants ($n = 2554$), only 9.6% fell within the “low” digital teaching competence category, 60.6% were in the medium category, and 29.8% were categorized as high [3]. Among the teachers responding to the specific question in this study ($n = 1505$), 8.4% fell into the low digital teaching competence category, 62.1% were classified as medium, and 29.4% were categorized as high. Thus, our study has a slightly larger proportion of teachers with medium competence compared to the overall survey results.

To assess for confidence bias, we examined whether teachers in schools with extensive experience in 1:1 computing reported lower digital teaching competence due to perceptions that their colleagues were more competent. Our comparison of the two quantitative measures revealed no evidence of confidence bias; teachers with long-term experience in

1:1 classrooms consistently scored higher in self-perceived digital teaching competence than those with shorter experience.

Nevertheless, we did observe a tendency toward an increased descriptive emphasis on classroom management in the cross-referenced qualitative and quantitative measures, as reported in the Findings section of this paper. This observation prompted a further in-depth qualitative analysis of the theme *Classroom Management*.

2.3.3. Phase 3: Reflexive Thematic Analysis of ‘Classroom Management’

To gain a deeper understanding of the focus on classroom management for “good teaching in the 1:1 classroom”, two researchers employed double coding (using NVivo 14) to analyze the 704 instances of coded statements related to classroom management through reflexive thematic analysis. This analysis is a creative, reflexive, and subjective process [51,52]. Themes do not pre-exist within the data; rather, they are actively constructed and related to one another by the researcher during the coding and analysis phases. The resulting themes emerge from reflexivity and interpretation [52,53]. Additionally, these themes do not encompass all complexities and variations in the data; instead, they offer a general understanding of the empirical material [54].

We initially coded the responses inductively within the overarching theme of classroom management, identifying ten distinct empirical focuses related to classroom management in “good teaching in the 1:1 classroom”. One primary category was “being a distinct or clear classroom leader”. However, many statements within this category lacked further elaboration, providing limited insight into their meaning. Consequently, we opted to exclude these statements and instead focused on more detailed statements within the other nine categories: (1) *Clear rules and regulations*; (2) *Clear structure; routines and framing*; (3) *Control through school software*; (4) *Control of access to technology*; (5) *Monitoring of student activity*; (6) *Discipline and consequences*; (7) *Clear goals and expectations*; (8) *Good relations*; (9) *Freedom under responsibility*.

We then employed an abductive approach [55] to construct themes, integrating relevant theoretical concepts related to aspects of classroom management the teachers emphasized within the data. This iterative process yielded three subthemes of classroom management, which are elaborated upon in the Findings section. (1) *Focus on student autonomy and involvement through preventive and student-centered strategies*; (2) *Balancing internal and external regulation, mostly through preventive but teacher-centered strategies*; and (3) *Focus on external control through different degrees of reactive strategies*. The reflexive and abductive analytical process also led us to develop a model that visualizes the different understandings and tendencies observed in the data.

2.4. Research Limitations

The open-ended question was survey question number 24 in a 25-question survey, which took approximately 15 min to complete. Out of 2410 informants, only 1505 chose to respond to this open question, potentially due to survey fatigue, which may introduce bias in both the respondents and the quality of their answers. However, those who responded to the question have a profile similar to that of the overall survey sample regarding 1:1 experience and self-reported digital teaching competence. The responses to the open question are slightly skewed toward grades 4–7, but this skew is less than 2% [49]. We recognize that short answers can weaken some qualitative findings, as interpreting terms such as “clear classroom management” can be challenging. In these cases, we have opted not to interpret the findings but instead to describe their occurrence. Furthermore, the teachers’ answers lack the specific context to draw on broader theoretical frameworks for interpretation. The abductive approach focuses the use of theory on what is empirically applicable and can thus be seen as a limitation to our study.

Generalization of our findings to the broader teacher population in Norway is not possible due to the strategic selection of the three regions with which the original research team collaborated. The teachers involved were already engaged in RPPs focused on digital

competence, which may differ from the average teacher population. However, these partnerships were intentionally chosen to qualitatively assess the perspectives of teachers with varying experiences in 1:1 computing regarding different aspects of digitalization, not for generalization.

Given that the survey was distributed digitally, teachers with higher digital competence may have been more inclined to respond. As noted, only 9.6% identified as having “low” digital teaching competence, while 60.6% categorized themselves as “medium” and 29.8% as “high”. Since there are currently no updated national statistics on teachers’ digital competence, we cannot compare these findings to national averages. However, because the goal of our study is to examine what teachers in schools at various stages of digitalization emphasize as essential for good teaching practice, the average digital competence among teachers is less significant than their qualitative perceptions of necessary competencies and practices.

3. Results

3.1. Five Main Themes for Good Practice in One-to-One Classrooms

The initial analysis of the aspects that teachers emphasized for good teaching practices in 1:1 classrooms resulted in five main themes, as detailed in Table 1.

Table 1. Themes on contributions to good teaching practices in 1:1 classrooms.

Theme	Description
<i>Teaching practice</i>	Includes statements that highlight the importance of a structured and balanced approach to classroom practice, integrating both digital and traditional methods. Emphasizes the need for variation, inclusion, and differentiation through assignments and tasks, as well as the regulation of digital resource use.
<i>Resources, access, and infrastructure</i>	Concern statements emphasize the importance of having reliable and accessible digital tools, resources, and systems to support both teaching and learning. Key aspects include stable internet access, resources and programs for differentiation, as well as systems and software for restricting access to certain resources or sites.
<i>Classroom management</i>	Encompasses statements that highlight the importance of establishing clear rules and expectations, fostering positive relationships with students, effectively structuring lessons, and maintaining focus and control within the classroom.
<i>Digital competence development</i>	Includes statements that focus on acquiring and enhancing the competencies necessary for the effective use of digital tools in educational contexts. It encompasses training for both students and teachers, the significance of continuous learning and school support structures, as well as the allocation of time for teachers’ professional development.
<i>Digital competence</i>	Includes statements that emphasize the necessity for both teachers and students to develop skills in utilizing digital devices and applications to enhance learning. For teachers, this entails familiarity with digital platforms, tools, and software, as well as the ability to effectively integrate them into lessons, often through collaboration. For students, in addition to technical competence, there is a need to cultivate critical thinking skills, such as evaluating sources, practicing netiquette, and understanding digital ethics.

3.2. Shift in Focus from Technical Issues to Classroom Management

Considering teachers’ self-perceived digital teaching competence and their experience with 1:1 computing, we identified a distinct descriptive tendency in the material.

First, we compared the main aspects emphasized by teachers with extensive experience in 1:1 computing to those with limited or no experience (with the introduction of 1:1 computing occurring between 2014 and 2022) (see Figure 1).

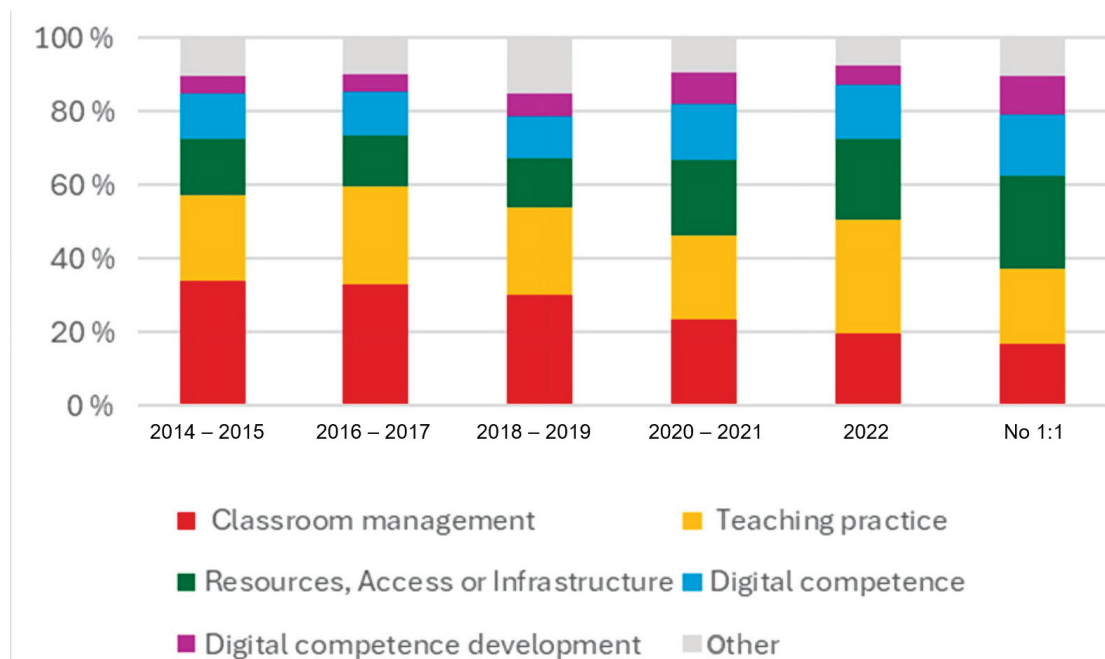


Figure 1. Cross-referencing focus themes with one-to-one experience.

Figure 1 illustrates that the largest shift in focus among teachers is contingent upon their experience with 1:1 computing, particularly between those who began teaching in 1:1 classrooms in 2014 and those who started in 2022 or had no experience (No 1:1). The shift occurs from a focus on Resources, Access, or Infrastructure (green) among the least experienced teachers to an emphasis on Classroom Management (red) among the most experienced. This shift is gradual; as teachers gain experience, the tendency implies that their focus increasingly shifts toward classroom management, while the other categories exhibit some variation over the years without a clear tendency.

Next, we descriptively compared the five most empirically coded aspects emphasized by teachers with self-reported low, medium, or high digital teaching competence (see Figure 2).

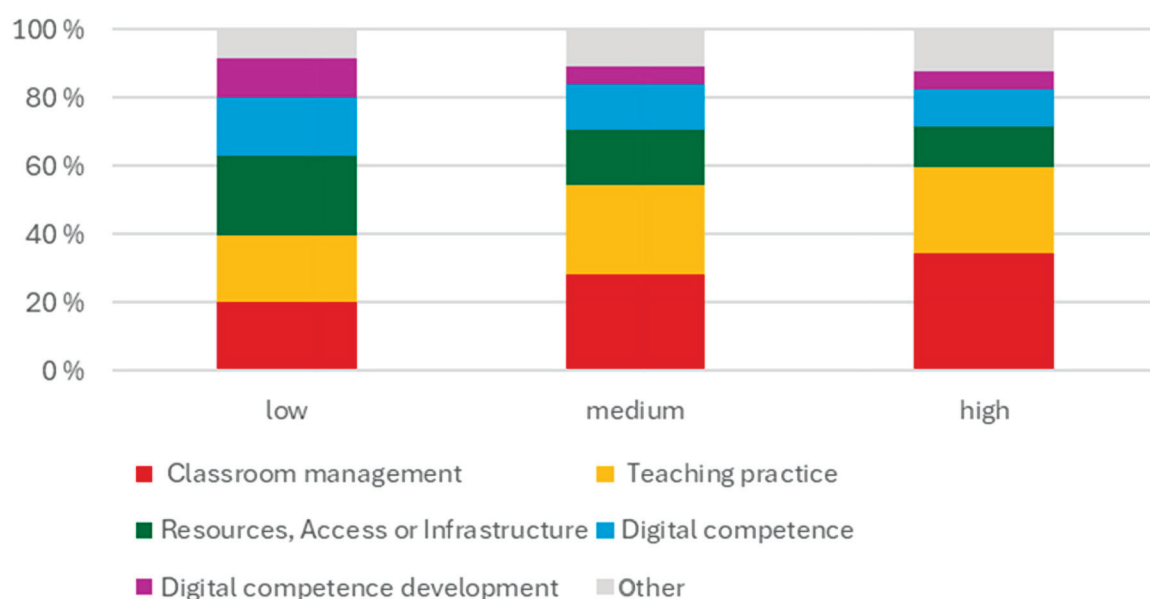


Figure 2. Cross-referencing focus themes with digital teaching competence perceptions.

In Figure 2, a similar tendency emerges as in Figure 1: teachers who consider themselves beginners or inexperienced in digital teaching competence (low) primarily emphasize technical aspects such as Resources, Access, or Infrastructure (green). In contrast, teachers who view themselves as experienced or experts (high) place the greatest emphasis on Classroom Management (red) when identifying factors that contribute to good teaching in 1:1 classrooms. Additionally, we observe a shift toward a greater focus on teaching practice among those with higher competence, alongside a diminishing emphasis on the need for digital competence and professional development among teachers who perceive themselves as highly competent.

In line with our exploratory research design, we opted to delve deeper into this main tendency—the shift from Resources; Access; or Infrastructure toward Classroom Management—by conducting a more thorough reflexive thematic analysis of what the teachers perceive as good classroom management.

3.3. Classroom Management in 1:1 Classrooms

The teachers emphasized various aspects of classroom management when explaining what contributes to good teaching in 1:1 classrooms, resulting in the construction of nine intertwined categories. Additionally, we identify two distinct underlying dimensions in their responses: a focus on student internal versus external regulation and a distinction between preventive and reactive management strategies, as illustrated in Figure 3.

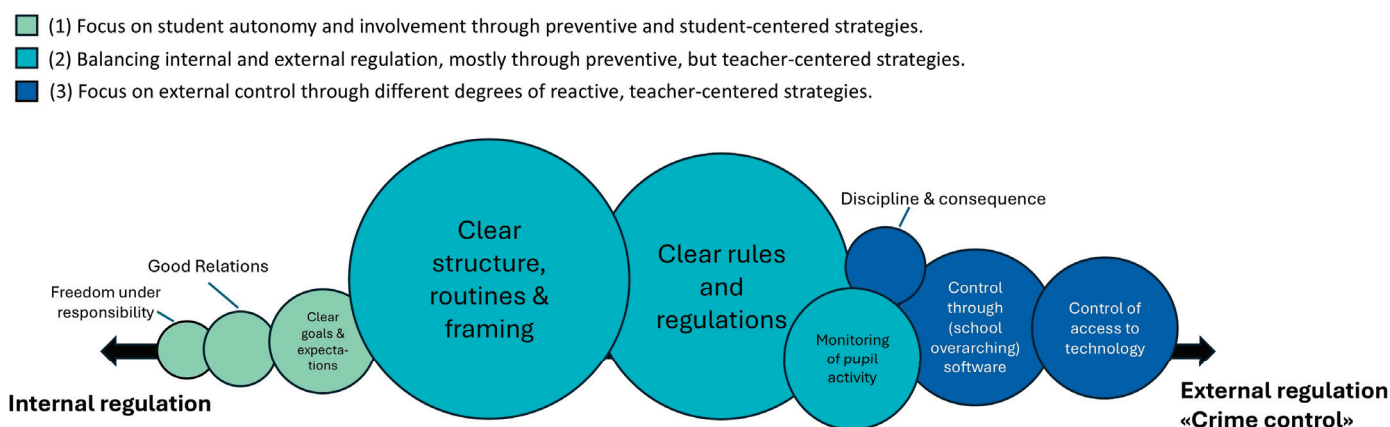


Figure 3. Visualization of interconnected themes and underlying focus on regulation.

The sizes of the circles indicate how often the categories were coded. Overlaps indicate that there are overlaps in the coding and a lack of clear borders between the categories. Based on their emphasis on internal or external regulation [39], we positioned the categories along a two-headed arrow: categories further to the left indicate a greater focus on internal regulation, while those further to the right represent a stronger emphasis on external regulation and crime control [40]. Additionally, we employed colors to denote the focus on preventive versus reactive strategies [38]. Statements emphasizing internal or self-regulation are represented in green (purely preventive), transitioning through turquoise (mostly preventive), to blue indicate tendencies toward or primarily reactive strategies in statements concerning external regulation. Consequently, we grouped the categories into three main subthemes related to classroom management for “good teaching in 1:1 classrooms”. (1) *Focus on student autonomy and involvement through preventive and student-centered strategies*; (2) *Balancing internal and external regulation, mostly through preventive but teacher-centered strategies*; and (3) *Focus on external control through different degrees of reactive strategies*. The themes are further described in detail.

3.3.1. Focus on Student Autonomy and Involvement Through Preventive and Student-Centered Strategies

We identified three categories in this sub-theme: Freedom under responsibility, Good relations, and Clear goals and expectations.

The three categories (Table 2) emphasize student-centered approaches aimed at fostering internal regulation and socio-emotional learning. Teachers employ preventive strategies to create a healthy and conducive learning environment. However, as indicated by the size of the circles in Figure 3, only a small number of teachers mentioned these approaches when discussing what contributes to good teaching in 1:1 classrooms. Frequently, they referenced these strategies in conjunction with practices that are characterized by teacher control and external regulation of student behavior. These combinations and overlaps are described in greater detail in the section titled “Overlaps”.

Table 2. Categories in sub-theme 1.

Category	Description
<i>Freedom under responsibility</i>	Refers to approaches that empower students by granting them responsibility and the opportunity to explore, choose topics and methods, and learn from their mistakes. This concept is articulated through responses such as “Allow students to explore and even make mistakes”, “A certain degree of freedom in choosing topics and methods for deeper learning”, and “Let students feel secure by exploring and, above all, allowing them to make mistakes”.
<i>Good relations</i>	Encompasses classroom management strategies that are founded on trust and respect between teachers and students, as well as among the students themselves. This emphasis is reflected in quotes such as “Trust between teacher and student”, “mutual trust”, and “Create a good class environment and good, healthy relationships between students and between the teacher and students”. Additionally, the category highlights the importance of establishing a positive and democratic learning environment. Teachers emphasized the need for “Building a positive classroom culture” and noted that students should be involved in defining rules, stating, “Students having a say in rule-setting”.
<i>Clear goals and expectations</i>	It involves teachers setting explicit objectives for students and guiding them on what is expected in their use of digital devices. This is illustrated by statements such as “Continuous communication about how digital devices should be used”. Establishing clear goals and expectations facilitates students’ ownership of their digital learning experiences, helping them stay on track. As one teacher noted, “Be clear about the goals and guide students along the way in the choices they make”. Additionally, teachers highlighted that these expectations serve as a means of granting students responsibility, stating, “Being clear on expectations and giving students responsibility”.

3.3.2. Balancing Internal and External Regulation, Mostly Through Preventive, but Teacher-Centered Strategies

This sub-theme consists of the categories of Clear structure, routines and framing, *Clear rules and regulations*, and *Monitoring of student activity*.

This sub-theme (Table 3) encompasses approaches that balance internal and external regulation. Clear structures and rules can facilitate internal regulation when students internalize them and recognize their purpose and significance. In such cases, these clear structures and rules may be viewed as preventive strategies. However, when combined with a teacher who actively monitors students, they take on characteristics of external regulation and behavior control, aimed at managing student behavior and intervening when necessary. Statements coded within this sub-theme, regardless of category, are characterized by a teacher-centered focus, indicating that it is crucial for the teacher to maintain control. A majority of teachers emphasize the categories in this sub-theme,

particularly *Clear Structure, Routines, and Framing* and *Clear Rules and Regulations*. Their prominence is underscored by the size of their circles in Figure 3.

Table 3. Categories in sub-theme 2.

Category	Description
<i>Clear structure, routines and framing</i>	Encompasses statements that underscore the necessity for teachers to provide structured guidance on the use of digital tools and learning applications. Typical quotes include "Clear boundaries for collective and individual focus", and "It's important to model the correct use of digital devices and apps, setting clear goals and criteria". Another example is: "Be consistent when it comes to establishing good routines for whether the screen is up or down. For instance, when the teacher is showing something on the smartboard, everyone follows along there, and the PC is mainly closed unless otherwise stated".
<i>Clear rules and regulations</i>	Emphasizes the importance of establishing clear, consistent teacher-led rules for the use of digital devices in classrooms. Typical quotes include: "There must be clear rules and routines for the use of devices. When and how they should be used", and "Teachers must control when and how devices are used". The goal is to promote focused learning by restricting access to non-academic content, as exemplified by the statement, "Clear rules to prevent distractions like social media or games".
<i>Monitoring of student activity</i>	Highlights the importance teachers place on actively overseeing what students are doing on their devices to ensure they remain on task and avoid distractions, what Kounin's calls "withitness" [43,44]. For instance, they express the need for "Following up on what students are doing and making sure they are not engaging in other 'nonsense'" and "Frequent checks to ensure students are doing what they should". Teachers emphasize the necessity of having an overview so they can intervene when a student requires assistance. This need is illustrated by quotes such as "The teacher must be able to see the students' screens", and "Monitoring from the back of the classroom and guiding the students who need it".

3.3.3. Focus on External Control Through Different Degrees of Reactive Strategies

This sub-theme consists of the three categories of Discipline and consequence, *Control through school software*, and *Control of access to technology*.

The categories in this sub-theme (Table 4) pertain to practices that externally control and regulate student behavior. In particular, control through software or requiring students to fold down screens at the teacher's command leaves little opportunity for the development of self-regulation. Depending on the context, these approaches can be preventive—such as when used as part of a routine during teacher-led explanations—or highly reactive; such as when implemented as punishment for rule violations or to "calm down" a classroom. Additionally, the enforcement of rules and consequences is primarily viewed as a reactive strategy. This sub-theme is characterized by a strong teacher-centered approach, with the teacher maintaining control to ensure appropriate behavior and manage discipline.

Table 4. Categories in sub-theme 3.

Category	Description
<i>Discipline and consequence</i>	Is closely related to rules and regulations. Teachers emphasize the importance of student discipline in adhering to these rules, stating, "Students must respect that digital tools are only used for what they are instructed to do". Furthermore, they highlight that there must be consequences for breaking rules. This category underscores the significance of discipline and accountability regarding the inappropriate use of digital tools. Typical quotes illustrating these points include: "It's important for students to know what's expected of them and the consequences of breaking the rules", and "Clear and explicit rules for the use of tablets. Consequences for breaking the rules are well known, and they are applied equally to all".

Table 4. Cont.

Category	Description
<i>Control through school software</i>	Conveys teachers' desire for software or tools that manage student use of digital devices, specifically to regulate what students can access during class. Teachers frequently note that students struggle to stay focused on their assignments and often drift off to browse the internet or use social media. As a result, they assert that effective teaching requires measures such as "Blocking access to non-educational websites", "Controlling student devices with programs that allow teachers to monitor usage", and "Shutting down access to distractions like social media and games".
<i>Control of access to technology</i>	Encompasses teachers' statements regarding the necessity of putting away digital devices or closing laptops to ensure students remain engaged in classroom activities. They assert that "Devices should be closed when attention is needed elsewhere", and emphasize the importance of having "Consistent routines for when screens are up or down".

3.3.4. Overlaps Between Categories

As indicated in Figure 3, there are overlaps in the coding. For instance, several teachers who discussed *Good Relations* also referred to *Clear Structure, Routines, and Framing*, or *Clear Rules and Regulations*, stating, "Good structure, order, and respect between teacher and student", and "Structure, order, respect, and a good relationship between teacher and student". Another example is the combination of *Clear Goals and Expectations* with *Control through Access to Technology*: "Closed screens while the teacher is speaking. Clear tasks and expectations". These overlaps demonstrate that teachers frequently integrate multiple practices and strategies. However, there appears to be a strong inclination towards external regulation, particularly teacher-centered approaches. Even when teachers mention preventive strategies that may promote internal regulation, they often couple these with external regulatory methods.

3.4. Summary of Findings

In summary, the empirical findings reveal several notable tendencies. First, extended experience with 1:1 computing appears to indicate a self-perception of having higher digital teaching competence; teachers with substantial experience consistently report higher competence.

Second, as teachers' digital teaching competence and experience with 1:1 computing increase, there is a shift in focus from technical issues and an instrumental approach to an emphasis on classroom management. Specifically, those reporting higher digital teaching competence tend to concentrate more on classroom management.

Third, the emphasis on classroom management across various competence and experience groups tends to prioritize external control through regulatory measures rather than fostering internal control through the development of student autonomy and digital self-regulation.

Fourth, while most teachers aim to integrate preventive and reactive strategies for effective 1:1 classroom management, a prevailing need for control is evident across nearly all themes. This contrasts with a smaller subset of teachers who prioritize relational aspects and the concept of freedom under responsibility, particularly in sub-theme 1.

4. Discussion

What aspects do teachers emphasize for good teaching practices in 1:1 computing classrooms, considering their self-perceived digital teaching competence and experience with 1:1 computing, and what challenges do these aspects present for professional development measures in RPPs?

4.1. Understandings of Digital Competence and Competence Development in Highly Digitalized Schools

When comparing our findings to previous research indicating that in-service teachers report varying levels of PDC [29,31,32] and often feel unprepared for teaching in technology-rich environments [9,10], highlighting a need for further competence development in this area [11], we observe several clear trends.

In our study, only 8.4% of teachers see themselves as having low digital teaching competence, while 62.1% had medium competence and 29.4% had high competence. Those who reported higher digital teaching competence also consistently reported more experience with 1:1 computing compared to their less competent peers. This could suggest that the teachers in our study equate digital teaching competence primarily with the technical skills required to use digital devices effectively in a 1:1 classroom setting. It appears that more experienced teachers have successfully navigated the first-order barrier of access and technical proficiency with digital devices [23], a finding that aligns with other studies on 1:1 computing in Norway [30,33].

The observed shift in focus from the need for digital competence development, resources, and infrastructure to an emphasis on classroom management (Figure 2) may reflect the belief among participating teachers that their technical skills suffice for achieving digital competence. In other words, these teachers are confident in their ability to use their tools and perceive this proficiency as sufficient for being digitally competent. This implies that the teachers may have a limited understanding of digital competence as mere technical proficiency. However, as mentioned, as digitalization in schools has increased, researchers' conceptions of PDC have extended beyond technical and digital teaching skills to include ethical, societal, and agentic aspects, such as classroom management specific to 1:1 teaching environments [3,7,8]. The teachers' perception of their high self-reported digital teaching competence and the subsequent lack of perceived need for further digital competence development thus pose significant challenges for RPPs.

The findings regarding digital competence suggest that existing competence development initiatives and RPPs may have concentrated too heavily on first-order barriers and instrumental measures. This focus may have given teachers a limited understanding, implying that PDC consists solely of generic and didactic skills [7]. Consequently, teachers with high self-perceived digital teaching competence may fail to recognize additional opportunities for enhancing their digital competencies, for instance in 1:1 classroom management.

4.2. Barriers for Good Teaching Practices in 1:1 Classrooms—Does Need for Control Hinder Good Practice?

If most teachers equate digital competence with the technical proficiency required to use digital devices and resources in the classroom, they may perceive teaching in 1:1 classrooms as analogous to teaching in traditional, non-digital settings. This perspective could lead them to apply the same classroom management strategies used prior to the implementation of 1:1 computing or struggle to adapt their approaches to the new environment, which represents a first-order barrier [23].

Classroom management encompasses both academic and social-emotional learning [35] and serves two primary objectives: (1) to create a quiet and orderly atmosphere that facilitates meaningful learning, and (2) to support students' social and moral growth [36]. Our thematic analysis reveals that the three classroom management sub-themes and their underlying categories (Figure 3) predominantly emphasize the first objective, focusing on regulations, structures, and tools for maintaining an orderly atmosphere. Conversely, teachers seldom address the second objective concerning social and moral development when discussing teaching in 1:1 classrooms.

The three sub-themes presented in Figure 3 are not distributed evenly. In fact, most teachers' responses are categorized under the second or third sub-themes, with very few focusing exclusively on internal regulation [39] through student-centered measures that foster digital self-regulation. Such measures include teaching social and emotional skills, building caring relationships with students [41,42], establishing firm and fair boundaries, and sharing responsibilities with students (sub-theme 1, Table 2). Instead, the majority of teachers emphasize a balance between internal and external regulation (sub-theme 2, Table 3), combining these strategies with techniques such as reinforcing desired student behavior through positive and negative reinforcement of clear rules and directions provided by the teacher [39]. Furthermore, the teachers emphasize strategies for "withitness" [43,44],

such as monitoring students' actions by walking around or standing in the back of the classroom. There is also a noticeable trend toward a focus on "crime control" through strict rules and the detection and punishment of "crimes" in theme 3 (Table 4) [40].

The shift toward classroom management associated with higher digital teaching competence and longer experience with 1:1 computing may indicate a movement toward second-order change [23], highlighting barriers such as teachers' beliefs—specifically their epistemic views regarding teaching methods and the utility of technology in the classroom [26,27]. Classroom management strategies are often linked to these beliefs, particularly regarding whether practices are teacher-centered or student-centered [27]. Our findings suggest that teachers may perceive 1:1 classroom management as necessitating a significant degree of teacher control and external regulation, a notion supported by previous research [17].

Similarly, while Moltudal et al. [34] identified four factors that must be balanced for effective classroom management in grade 11–13 Norwegian 1:1 classrooms, our findings primarily highlight two of these factors in the context of grade 1–10 classrooms. Specifically, Moltudal et al.'s [34] categories of *Control and Structure* and *Managing Non-Academic ICT Use* are prominent and can be related to both sub-themes 2 and 3. The factor *Managing Non-Academic ICT Use* identified by Moltudal et al. [34] is approached through distinct measures in our study, with most teachers balancing preventive and reactive strategies. However, this factor is also framed as the students' responsibility, particularly in sub-theme 3. Our findings suggest a tension between the responsibilities of teachers and the expectations placed on students. While students are expected to manage their behavior, especially in adhering to rules for digital device usage—illustrated by teacher comments such as "students must respect that digital tools are only used for what they are instructed to do" in the category of *Discipline and Consequences* within sub-theme 3 (Table 4)—the data indicates that teachers may assume students will inherently follow these guidelines without adequate support. A small minority of teachers emphasize the need for training in self-regulation, with this focus primarily evident in sub-theme 1 and the category *Clear Structure, Routines, and Framing* within sub-theme 2 (see Table 3).

However, the factor of *Teacher-Student Relationships* identified by Moltudal et al. [34]—which they consider crucial for mitigating disruptions and enhancing engagement with digital tools—is scarcely mentioned in our data; aside from a few statements from teachers within sub-theme 1. Similarly, their factor of *Adaptation and Flexibility*, linked to the integration of technology by teachers with higher competence, does not emerge as a distinct category or theme in our findings.

These observations may suggest two possibilities: First, teachers self-classified as medium or highly competent may not have yet developed digital classroom management practices that prioritize *Teacher-Student relationships* or incorporate *Adaptation and Flexibility*. Self-perceived digital teaching competence is not an objective measure, and these findings could reflect a focus on technical skills and first-order barriers related to digital competence. Second, these factors might either represent tacit knowledge, go unrecognized as specific to 1:1 classrooms, or fall within the broader category of *Distinct Classroom Management* that we could not interpret clearly.

Nevertheless, these findings reveal a potential gap in classroom management within our study, where teachers may be distancing themselves from the active role required to help students internalize expectations through preventive strategies in 1:1 classrooms. The expectation that students will "just understand" the rules—prevalent in themes 2 and 3—overlooks the necessity for teachers to consistently teach; reinforce; and model desired behavior within relationships built on mutual trust. Fostering students' social and moral growth in their use of digital devices and resources could be enhanced by prioritizing *Teacher-Student relationships* and by modeling and practicing student self-regulation from an early age.

More socially and morally developed, or self-regulating, students would also facilitate greater *Adaptability and Flexibility* in teaching, as the need for control or reactive measures

diminishes [34]. As noted by Tømte et al. [33], regulating access to resources such as YouTube poses challenges for both teachers and students in 1:1 classrooms, limiting the teaching capabilities of even those with high PDC and hindering students' opportunities to develop their digital responsibility and self-regulation.

4.3. Classroom Management in the 1:1 Classroom—Is It the Students' Responsibility to Learn How to Self-Regulate Digital Use?

Classroom management encompasses a range of practices and strategies that teachers can integrate to foster a conducive learning environment [37]. In summary, our findings indicate that the teachers in the highly digitalized schools in our selection do not necessarily employ a wide array of practices and strategies for classroom management when suggesting what contributes to good teaching in 1:1 classrooms. According to Korpershoek et al. [38], all five types of practices aimed at achieving high-quality classroom management are represented in our study, but to very different degrees.

The teachers focus on organizing and delivering instruction to maximize students' access to learning (practice 2) and foster engagement in academic tasks through group management methods, such as establishing rules and procedures (practice 3), primarily within sub-theme 2: *Balancing internal and external regulation*, mostly through preventive, but teacher-centered strategies. They also apply appropriate interventions for students with behavioral issues (practice 5), particularly in sub-theme 3: *Focus on external control through different degrees of reactive strategies* (Table 4).

However, practices aimed at building caring and supportive relationships with students (practice 1) and promoting the development of students' social skills and self-regulation (practice 4) mainly appear within our first sub-theme: *Focus on student autonomy and involvement through preventive and student-centered strategies*. Thus, only a small fraction of teachers' statements emphasize the importance of building positive relationships and fostering student responsibility for behavior as key components of good teaching in 1:1 classrooms. This suggests that such practices are either under-communicated or perceived as less important compared to more teacher-centered approaches. Consequently, the findings indicate that the teachers may not adequately teach students how to self-regulate their digital practices, causing the need for the same management strategies independent of educational level. If the students do not learn digital self-regulation, teachers cannot use a broader range of teaching strategies and management practices that rely on mutual trust and inner regulation.

5. Concluding Implications for Professional Development and Further Research

Our research provides practical insights into the nuanced focuses of a specific group of teachers navigating digitalization in highly digitalized schools. We hope that the experiences and understandings of these Norwegian teachers offer valuable lessons for countries at earlier stages of digital implementation in education. The implications of the challenges in our findings for professional development measures in RPPs are threefold.

First, RPPs must adopt a broader understanding of teachers' PDC, extending beyond the first-order barriers of access, resources, and infrastructure, as well as the technical use of digital devices in the classroom. Especially, our findings indicate that RPPs for teachers with higher digital teaching competence must address broader perspectives and second-order barriers, especially in classroom management [23]. Our findings suggest that RPPs may have previously concentrated too heavily on first-order barriers and instrumental measures across all competence levels, leading teachers to overlook further opportunities for digital competence development. This aligns with research on PDC development in Norway, which indicates a tendency among both pre-service and in-service teachers to focus on instrumental aspects such as technical proficiency [8,15].

Second, RPPs should address all facets of classroom management, equipping teachers with broader perspectives and preventive strategies that promote internal regulation in navigating 1:1 classroom management. A key focus area should be on teacher-student

relationships and fostering adaptability and flexibility in practice through caring relationships and mutual respect, where teachers provide support while also establishing clear expectations for their students.

Third, RPPs must systematically implement strategies to teach students digital self-regulation. Development measures should concentrate on teaching, reinforcing, and modeling desired student behaviors from an early age, utilizing systematic approaches tailored to different grade levels. These measures should prioritize classroom management that emphasizes teacher-student relationships, mutual trust, and social and moral growth—encompassing continuous social-emotional learning.

Future research should focus on more in-depth qualitative approaches such as interviews and observation studies to provide deeper insights into how teachers approach and understand classroom management in 1:1 classrooms. Based on our implications, future digitalization initiatives internationally should develop implementation models that integrate digitalization with PDC development in schools, emphasizing a broad understanding of digital competence and classroom management. Additionally, effective methods for systematically training students in digital self-regulation from an early age should be explored further.

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Article

Teachers' Participation in Digitalization-Related Professional Development: An International Comparison

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Abstract: The global digital transformation poses challenges for schools and teachers. The importance of digitalization-related professional development (PD) in overcoming these challenges is widely recognized, even if only few studies confirm the desired success. This article explores the relationship between the participation of teachers in digitalization-related PD and variables that are associated with successful PD in an international context. The structural equation modeling analyses are based on data from the International Computer and Information Literacy Study (ICILS 2018). Data from Chile (N = 1682 teachers), Denmark (N = 1108), Germany (N = 2303), the Republic of Korea (N = 2122), and the USA (N = 3174) are considered. These five countries are located on four different continents and have divergent conditions for working with ICT in schools and teacher PD. The results reveal significant relations between the participation in digitalization-related PD and positive views on using ICT in schools, the emphasis on promoting ICT-related skills among students, and the frequency of the use of ICT in the classroom across all countries. These findings demonstrate the importance of PD in the context of the digital transformation in schools, irrespective of international variations in school systems, digitalization processes, and conditions for PD.

Keywords: professional development; teacher professionalization; ICT; ICILS; international comparison

1. Introduction

Due to various megatrends such as globalization and digitalization, the world is in state of constant change. Among other things, far-reaching reforms of education systems are being initiated worldwide, leading to changes in teaching and learning in schools (Bautista & Ortega-Ruiz, 2015). Information and communication technologies (ICT) are considered a key factor worldwide, although their potential in education is far from exhausted (Fernández-Batanero et al., 2022). There is a consensus that teachers have an important role to play in the process of implementing ICT in teaching and learning processes (OECD, 2015; Wohlfart & Wagner, 2023). To play this role, teachers need to be adequately prepared to use ICT in school (Starkey, 2020). They need to have sufficient digital skills themselves, while being able to teach digital competences to students (Esteve-Mon et al., 2020). Due to their enormous importance, digital competences should already be taught as part of teacher training (Howard et al., 2021). However, as digitalization continues to advance and new technologies and digital opportunities are constantly emerging, basic ICT training for teachers is not enough. Teachers need to receive continuous professional development (PD) on the topic (Redecker, 2017; UNESCO, 2018).

Given the actuality and importance of the topic, researchers have been increasingly focused on digitalization-related teacher PD in recent years. There are several studies on such teacher PD in various countries, often focusing on the impact of individual PD courses (An, 2018; Lucas et al., 2021). What is currently lacking, however, are studies that examine not only the impact of individual digitalization-related teacher PD courses but also the overall effectiveness of participation in PD on a larger scale, building on representative data to produce reliable results on the importance of lifelong learning in formal PD settings to enhance ICT-related teaching quality. On the other hand, there is also a lack of studies that examine the effectiveness of digitalization-related teacher PD in an international comparison.

This article examines the relationship between participation in digitalization-related PD for teachers and teachers' perceived PD success in five different countries: Chile, Denmark, Germany, the Republic of Korea, and the United States. It describes the national contexts for the use of ICT in schools and builds on Merchie et al.'s (2018) extended evaluative framework for mapping the effects of PD initiatives and the current state of research. Using data from the International Computer and Information Literacy Study (*ICILS 2018*; Fraillon et al., 2020), descriptive and inferential analyses of PD participation and structural equation modeling to examine the effects of PD in the countries are conducted and discussed.

2. National Contexts for the Use of ICT in Schools

The following chapter provides background information on the ICT-related macro-societal conditions and the micro-context based on the *ICILS 2018* data for Chile, Denmark, Germany, Korea, and the USA. Denmark was chosen as a comparison country because its students have the best computer and information-related skills (Fraillon et al., 2020). The other four countries were chosen, in part, to provide a comparison between four different continents, thus providing a global perspective on the issue. In addition, the five countries differed in terms of ICT-related macro-societal conditions and micro-context, as will be shown below. This broad selection of countries increases the generalizability and applicability of the study results in a broader context.

In terms of macro-societal conditions, there are differences between the five countries in terms of curricula related to digital literacy. In Chile, there was a separate compulsory CIL-related subject in 2018, while other subjects that integrate ICT are not compulsory. In Korea, on the other hand, it was still a separate compulsory elective subject until the *ICILS 2018* survey but will become a separate compulsory subject in the future. In Denmark and Germany, on the other hand, there was no separate subject until 2018, but ICT should be integrated into all subjects. In the USA, on the other hand, districts and schools are free to choose whether to introduce a separate CIL-related subject or to integrate ICT into all subjects (Fraillon et al., 2020).

Furthermore, there are few differences between the countries in the description of plans and policies for the use of ICT in education. However, a closer look at the micro-context reveals differences in their implementation, particularly with regard to IT resources in schools in the five countries. *ICILS 2018* recorded the technology-related and software-related resources for teaching and learning, as well as the availability of technology facilities for teaching and learning in the countries. It turns out that Denmark has the best IT resources in overall. In Korea, it depends very much on the resources considered, so it can be classified as moderate overall. In Chile and Germany, on the other hand, the level of IT resources is comparatively low (Fraillon et al., 2020). It should also be noted that Chile places a higher priority on facilitating the use of ICT in education than Denmark, Germany, and Korea (Fraillon et al., 2020). The USA does not meet the high participation

requirements of the ICILS sample for a comparison across all aspects. However, in *ICILS 2018*, they show a fairly good overall availability of IT resources and place a high priority on facilitating ICT-use in teaching and learning (Fraillon et al., 2020).

3. Extended Evaluative Framework for Mapping the Effects of Professional Development Initiatives

In many countries around the world, initial training is considered a basic requirement for entering the teaching profession. However, it is only the first step in professionalization, as teachers should continue to develop throughout their working lives (Stürmer & Seidel, 2017). There is a wide range of activities and interactions that can fall under the term professional development (Desimone, 2009), which is why there is no standard definition of the term (Merchie et al., 2018; Sancar et al., 2021). However, at its core, professional development is always about “teachers learning, learning how to learn, and transforming their knowledge into practice for the benefit of their students’ growth” (Avalos, 2011, p. 10). Depending on the concept of PD used, either only formal learning (Darling-Hammond et al., 2017; OECD, 2009) or also informal learning activities (Borg, 2018; Lee et al., 2019; Watters, 2014) are considered. In the following, based on the definition by Darling-Hammond et al. (2017, p. V), we understand digitalization-related professional development as structured professional learning with and about ICT that can lead to changes in teachers’ attitudes and practices and, as a consequence, to improvements in student learning outcomes.

The present article aims to contribute to the investigation of the success of teachers’ participation in digitalization-related PD in various countries. The evaluative framework for mapping the effects of PD initiatives by Merchie et al. (2018) that is displayed in Figure 1 serves as the theoretical basis for deriving relevant outcomes. In recent years, various theoretical and analytical frameworks have been developed to improve the understanding of teacher PD, its framework conditions, and its effects (Njenga, 2023). The model by Merchie et al. (2018) is an extension of the core conceptual framework by Desimone (2009) which is a widely used model related to the effects and goals of PD.

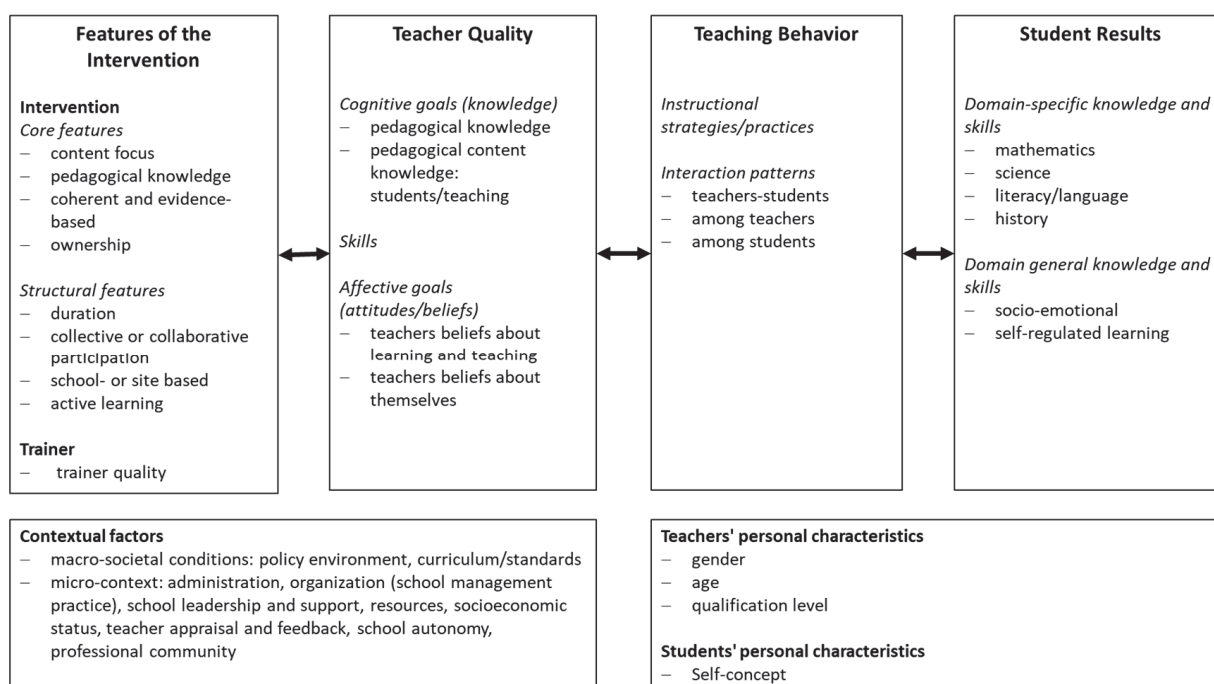


Figure 1. Extended evaluative framework for mapping the effects of professional development initiatives (Merchie et al., 2018).

According to the model, teacher PD consists of four steps (Desimone, 2009). First, teachers take part in an effective PD intervention. Effective teacher PD can be identified by various core features (substance) and structural features (structural and design characteristics) as well as trainer quality (Merchie et al., 2018). Whether participation in a PD course was effective can also be determined by the outcomes of participation. The initial focus here is on changes in teacher quality. A distinction is made here between changes in cognitive goals (knowledge), affective goals (attitudes and beliefs), and teacher skills (Merchie et al., 2018). The third component is changes in teaching behavior as a result of participation in PD. These can take the form of changes in teachers' instructional strategies and patterns or in patterns of interaction with and among teachers and students. The fourth component of the framework is improvements in student outcomes. Here, the focus is on improvements in domain-specific knowledge and skills as well as domain-general knowledge and skills (Merchie et al., 2018).

In addition to these four core components, contextual factors are also relevant to the success of teacher PD, according to the framework by Merchie et al. (2018). This is of central relevance for the present study, which examines the relationship between participation in digitalization-related PD and the selected outcomes, considering the different national framework conditions in five different countries. Next to macro-societal conditions, aspects at the micro-context level are also considered in the model. Personal characteristics of teachers (e.g., gender and age) and students also play a role in the impact of PD participation (Merchie et al., 2018).

Building on the presented theoretical model, this article examines the relationship between digitalization-related PD on different ICT-related topics and various aspects of teacher quality and teaching behavior. Teacher quality is measured by positive views on using ICT in teaching and learning, while teaching behavior is assessed through the emphasis on promoting ICT-related skills among students and the frequency of the use of ICT in the classroom. This selection of constructs ensures that the key outcomes of successful PD, as identified by Merchie et al. (2018), are considered and tested in an international sample. Special attention is paid to differences in teacher PD and ICT integration across countries, which will be described in more detail below. By analyzing data from Chile, Denmark, Germany, Korea, and the USA, the study examines variations in the frequency of PD participation and its effects across diverse educational contexts. Additionally, teachers' personal characteristics are considered as control variables.

4. Participation in Professional Development Activities: Numbers, Requirements, and Obstacles

The UNESCO (2018) competency framework for teachers highlights the need for teachers to receive technological training as part of their PD. However, participation in PD activities of any kind requires appropriate contextual conditions such as the availability of suitable learning opportunities and organizational support. Results from *TALIS 2018* show that the most common obstacles to participation in PD activities are work schedules (considered as a barrier by 54% of the teachers across all TALIS countries) followed by the lack of incentives and cost of participation (OECD, 2019). The opportunities available to teachers are strongly influenced by national and school policies (Desimone, 2009; Njenga, 2023). In some countries, the availability of adequate courses and training to acquire digital competence¹ is low (e.g., Germany: Mauss, 2020).

Overall, PD requirements vary from country to country. In Germany, teachers are required to participate in PD on a regular basis (OECD, 2022; Wendt et al., 2016). In the USA, most states also require PD to renew a teacher's license (Malley et al., 2016). In Korea, PD in specific areas is mandatory for all teachers. In addition, participation in PD in other

areas is mandatory for promotion or salary increases (OECD, 2022). In Chile, there is no obligation to participate in PD. However, participation is also mandatory for promotion or salary increases (OECD, 2016). In Denmark, there are no official requirements for PD. In this country, school leaders are responsible for the PD of their teachers (Allerup et al., 2016; OECD, 2022).

As with requirements, the level of support and access for teachers to participate in ICT-based PD varies from country to country. This can be seen as a particularly important issue for PD as some practicing teachers have not benefited from exposure to technology in their pre-service training (UNESCO, 2018) or feel inadequately prepared by their ICT training during their teacher education (Gudmundsdottir & Hatlevik, 2018). Looking at support for six different areas of PD (see Table 1), a survey conducted as part of *ICILS 2018* revealed the following for the five countries considered in this article: Germany only provides resources that teachers can access for all six areas, while Chile also funds teacher participation. In Denmark and the Republic of Korea, relief teachers are provided in addition to the two supports so that teachers can participate in ICT-based PD in the six areas. In the United States, on the other hand, all three types of support are provided for only three of the areas, while no relief teachers are provided for the other three. For one of these areas, additionally, no funding is offered (Fraillon et al., 2020).

Table 1. Level of support for teacher access to and participation in ICT-based professional development.

Country	Chile	Denmark	Germany	Republic of Korea	USA
To improve ICT/technical skills	● Δ	● Δ ◇	Δ	● Δ ◇	● Δ ◇
To improve content knowledge with respect to computer information literacy (CIL)	● Δ	● Δ ◇	Δ	● Δ ◇	● Δ ◇
To improve teaching skills with respect to CIL-related content	● Δ	● Δ ◇	Δ	● Δ ◇	● Δ ◇
To develop digital teaching and learning resources	● Δ	● Δ ◇	Δ	● Δ ◇	Δ
To integrate ICT in teaching and learning activities	● Δ	● Δ ◇	Δ	● Δ ◇	● Δ
To improve skills in computer programming or developing applications for digital devices	● Δ	● Δ ◇	Δ	● Δ ◇	● Δ

● By funding teacher participation in programs. Δ By providing resources for teachers to access. ◇ By providing relief teachers to allow regular teachers to attend programs. Source: Fraillon et al. (2020, p. 39) shortened by the authors.

Not least, due to different availabilities and requirements, the amount of teacher involvement in PD activities varies across countries. According to *TALIS 2018*, both the USA and Korea are above the average of 31 OECD countries in terms of the percentage of lower secondary teachers who participated in PD activities in the 12 months prior to the measurement (OECD average around 94%). Both values are around 98 percent, with a slightly higher percentage in the USA. Denmark (about 92%) and Chile (about 87%) are below the OECD average (OECD, 2019). Germany was not included in this study. However, older findings from *GEW 2008* (equivalent to *TALIS 2008*) show that Germany was above the international *TALIS* average for PD participation at that time (about 99% vs. about 90%) (GEW Deutschland, 2009). In terms of different types of PD, students in Denmark are less likely to be taught by teachers who have spent time on ICT-related professional learning in their own time but more likely than the EU average to be taught by teachers who have participated in school-provided ICT training, compulsory ICT training, and online communities for professional discussions with other teachers (European Commission,

2019). In line with a previous study for the European Commission (2013) in 2013, more recent results confirm that across the European Union, equipment-specific training, subject-specific training on learning applications, and pedagogical courses on the use of ICT are used to a similar extent (European Commission, 2019).

In the review of teachers' various PD activities across different countries, the literature suggests that participation varies with teachers' individual characteristics such as age and gender (Njenga, 2023). However, results from *TALIS 2008* (OECD, 2009) and *TALIS 2018* (OECD, 2019) suggest that on average across the participating countries, teachers' participation in PD does not differ significantly between men and women, although there are small differences in many countries. In Germany, studies also show no significant gender differences in participation (Richter et al., 2010).

According to *TALIS 2008* data, teacher age had a significant impact on the number of days of PD, with younger teachers under the age of 30 receiving approximately 21 days of PD and teachers over the age of 50 receiving approximately 14 days over the 18-month period (OECD, 2009). These significant age differences can be found in Denmark and Korea, among other countries (OECD, 2009). In Germany, however, there is mixed evidence on age differences: According to Richter et al. (2010), younger teachers are more likely, and according to Kuschel et al. (2020), less likely to participate in PD activities than older teachers. As stated by Richter et al. (2011), the frequency of PD is further described as U-shaped, which may explain the divergent findings.

5. Effects of Professional Development Activities

According to Desimone (2009) and Merchie et al. (2018), the success of PD depends on the characteristics of the particular intervention, program, or course. Many different forms of formal face-to-face or virtual PD can be distinguished, such as mentoring, coaching, and workshops (Bautista & Ortega-Ruiz, 2015; Watters, 2014). The respective formats are known to differ in their effectiveness (Kiel et al., 2014; Qasem & Viswanathappa, 2016; Waffner, 2020). Some PD programs appear to be successful in improving teacher competence and classroom practice, especially when they use "features of high-quality PD" (Bautista & Ortega-Ruiz, 2015). For example, there is evidence that "shows that success factors for PD activities are a high content focus, active learning, sustained duration, collective participation, coherence, and ownership" (European Commission, 2023, p. 18).

Regardless of the design of the particular intervention, a core goal of PD is to strengthen teacher quality. In terms of ICT, PD programs can focus on enriching technological, pedagogical, and content knowledge (TPACK; see, e.g., Rodríguez Moreno et al., 2019); increasing self-efficacy; fostering a more positive view of digital progress in schools; and improving the ability to use different digital tools effectively. As Mannila et al. (2018) note, it is not enough to simply increase knowledge of computing content through isolated, in-service training initiatives. Rather, teachers also need to develop high self-efficacy in order to have the "confidence to independently and continuously explore what is new, what is relevant, and how to include digital competence in their teaching" (Mannila et al., 2018, p. 78). Several studies have demonstrated the positive impact of PD on digitalization-related teacher quality (An, 2018; Hardré et al., 2014). For example, according to Prestridge (2010), ICT-related PD, especially when it engages teachers in constructive dialogue, has the potential to transform Australian teachers' beliefs. In line with this, Pongsakdi et al. (2021) showed that digital pedagogy training can shape in-service teachers' attitudes towards digital technologies in a sample of Finnish elementary and lower secondary school teachers. In particular, the training helped teachers with low confidence in ICT to gain confidence. In German-speaking countries, Thurm (2020) found that teachers' technology-related beliefs developed more favorably through participation in PD on ICT. In addition, there are several

consistent findings that participation in digitalization-related professional development has a positive effect on self-efficacy beliefs about one's competence in using ICT in school (Drossel & Eickelmann, 2017; Runge et al., 2022a, 2022b). Reisoğlu (2022) showed that a collaborative and applied digital competence training in creating interactive e-books enhanced the knowledge and skills of Turkish teachers in various teaching-related areas. According to Albion et al. (2015), any approach to ICT-related teacher PD should focus on teachers' pedagogical beliefs as they have a significant relationship with the actual use of ICT in the classroom (Drossel et al., 2016; Haixia et al., 2018; Hermans et al., 2008; López-Pérez et al., 2019).

The theoretical model furthermore suggests that successful digitalization-related PD has an impact on teachers' behavior, including their instructional practices and interactions with students and other teachers (Merchie et al., 2018). Improving teachers' self-assessed digital competence, including knowledge and attitudes, through PD is known to influence the frequency of their use of ICT in the classroom (Guggemos & Seufert, 2021; Ramírez-Montoya et al., 2017). The impact of PD activities on teachers' professional practices has been analyzed in several studies. For example, An (2018) demonstrated that participation in a PD course at a public university in the USA positively influenced teachers' behavioral intentions regarding the use of digital games in the classroom as well as their support for other teachers to integrate digital games in the classroom. In Reisoğlu's (2022) study, teachers improved their communication and collaboration using digital technologies by receiving digital competence training. The studies by Drossel and Eickelmann (2017), Runge et al. (2022b), and Runge et al. (2022a) show that participation in digitalization-related PD not only leads to more frequent use of ICT in the classroom by teachers but also to a higher quality of teaching when using ICT. It has also been shown that teachers attach more importance to teaching 'digital' competences after participating in digitalization-related PD than before (Drossel & Eickelmann, 2017).

An ultimate goal of teacher PD activities is to impact student achievement (Watters, 2014). However, while some studies find an impact of teacher PD on student achievement (Koh et al., 2017; Sancar et al., 2021), a number of other studies find no significant impact (Bautista & Ortega-Ruiz, 2015).

Finally, the success of PD is influenced by several contextual and individual factors. For many countries, reviews of empirical studies show that PD activities to improve teachers' technological competence have low availability (Fernández-Batanero et al., 2022) and lack efficiency (Dağ, 2016). Research also suggests that the effectiveness of PD depends not only on its format and quality but also on the physical, socio-cultural, and organizational contexts, such as educational systems and policies, including the resources available for PD (Darling-Hammond et al., 2017; Lee et al., 2019). However, to date, no studies have compared the effectiveness of PD across countries.

6. Objectives and Research Questions

This article investigates digitalization-related PD for teachers. First, based on large representative samples of the *ICILS 2018*, the frequency of participation in five different countries is examined and compared. In contrast to other international comparisons available so far (OECD, 2019), various ICT-related PD contents are taken into account. The research is guided by the following question:

RQ 1. *How does the reported participation of teachers in professional development on various ICT-related topics differ between Chile, Denmark, Germany, the Republic of Korea, and the United States?*

Despite a lack of international empirical research, the participation rates are expected to vary across countries due to contextual differences. Denmark is expected to have

high participation rates because teachers of all subjects are required to integrate ICT into their teaching. In addition, participation is extensively supported, and there are good IT resources in schools to practice. Participation is also expected to be high in the USA, as schools have good IT resources and prioritize facilitating the use of ICT in teaching and learning. In addition, PD is generally mandatory for teachers, and support for digitalization-related PD is moderate. In Korea, support is extensive, but IT resources are moderately available. Since it is also not mandatory for all teachers to integrate ICT into their subjects, Korea is expected to have a medium participation rate. The same is expected for Germany. Although the integration of ICT in all subjects is mandatory, the level of support for participation is rather low, and the IT resources in schools are comparatively poor. Chile is expected to have the lowest participation because teachers are not required to use ICT in all subjects, schools do not have good IT resources, and support for participation is mediocre. Nevertheless, methods to facilitate the use of ICT in teaching and learning are a high priority.

The respective hypotheses are as follows:

H1a. *Denmark and the United States have the highest participation rates within the sample.*

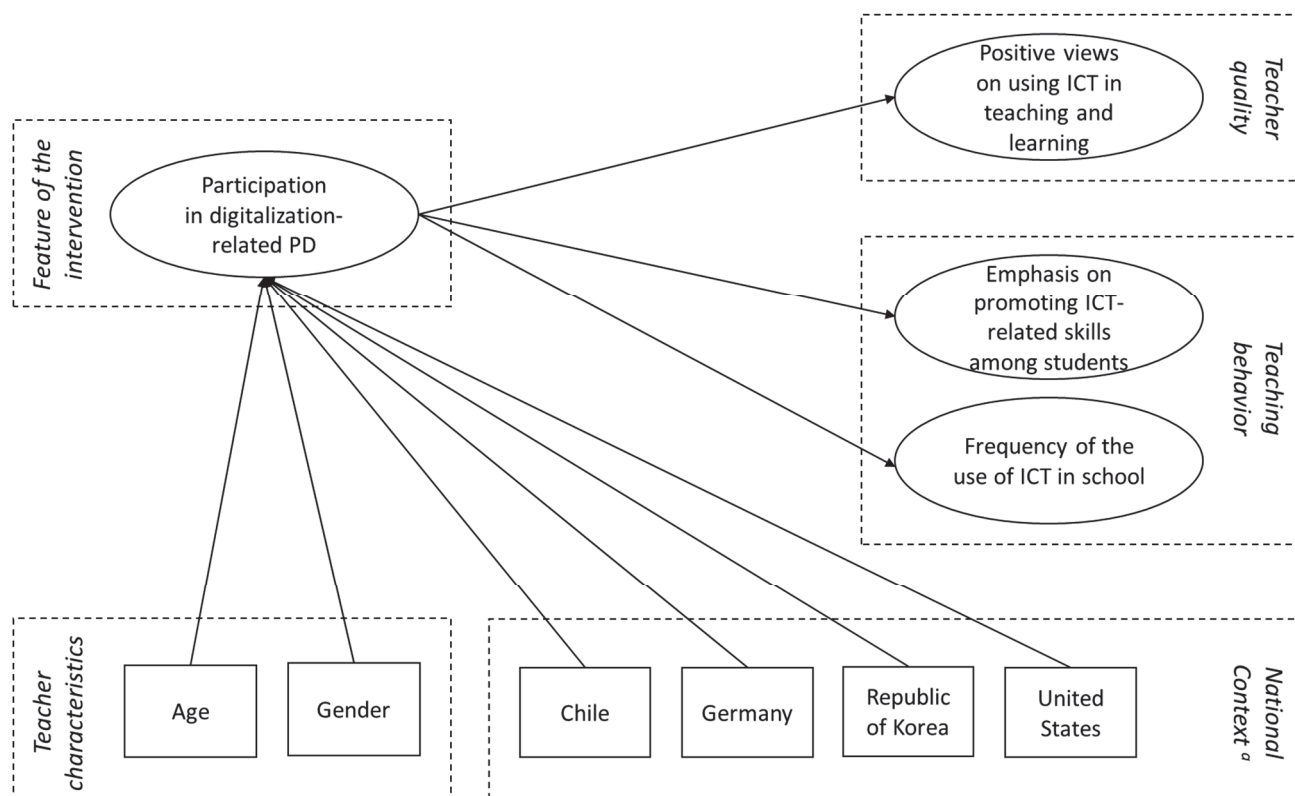
H1b. *Korea and Germany have moderate participation rates.*

H1c. *Chile exhibits the lowest participation rate within the sample.*

The second part of this study focuses on the connection between PD activities and its potential outcomes. In the previous chapter, findings on the impact of selected PD programs were reported. However, most of the studies cited refer to individual, geographically limited programs. In contrast, there is very little material incorporating different countries with a large representative sample. Based on this, the second research question examines the relationship between participation in ICT-related PD and the aforementioned characteristics of effective PD in the five countries considered:

RQ 2. *What is the relationship between reported participation in digitalization-related professional development for teachers and perceived characteristics of professional development success in Chile, Denmark, Germany, the Republic of Korea, and the United States, and are there differences across countries?*

Despite the distinction between more and less successful activities in terms of life-long learning, a general positive relationship between formal learning opportunities on a particular topic and corresponding beliefs, skills, and classroom behavior can be expected for the international sample of teachers analyzed in this study. In line with the theoretical model of Merchie et al. (2018) and based on various individual empirical studies conducted globally, we assume that participation in digitalization-related PD is reflected in a more positive view on using ICT in teaching and learning (i.e., more positive beliefs; see, e.g., Prestridge, 2010; Thurm, 2020), a greater emphasis on promoting ICT-related skills among students, and a greater use of ICT in the classroom (An, 2018; Drossel & Eickelmann, 2017; Guggemos & Seufert, 2021; Ramírez-Montoya et al., 2017; Runge et al., 2022a, 2022b). These assumptions extend to all the countries included in the study, even though the state of research presented does not contain findings on all areas. The corresponding analytical model is shown in Figure 2.



^a The reference category for the national context is Denmark.

Figure 2. Analysis model of our research.

As personal characteristics are also expected to influence the participation in and effectiveness of PD (Merchie et al., 2018), teachers' age and gender are controlled for in the models. Previous studies have found small, but mostly insignificant, age and gender differences in teacher participation across different countries (OECD, 2009, 2019).

The respective hypotheses are as follows:

H2a. *There is a positive relationship between the participation in digitalization-related PD and teachers positive views on using ICT in teaching and learning in the five countries.*

H2b. *There is a positive relationship between the participation in digitalization-related PD and the emphasis on promoting ICT-related skills among students in the five countries.*

H2c. *There is a positive relationship between the participation in digitalization-related PD and the frequency of the use of ICT in the classroom in the five countries.*

H2d. *The anticipated relationships are also observed when each country is analyzed individually.*

7. Materials and Methods

7.1. Data Basis

To answer the research questions, secondary analyses will be conducted using data from the teacher questionnaire of the International Computer and Information Literacy Study (ICILS 2018, e.g., Fraillon et al., 2020). ICILS is coordinated by the International Association for the Evaluation of Educational Achievement (IEA) and aims at an international comparison of the computer and information literacy (CIL) of eighth grade students. As part of the study, extensive background questionnaires were used to capture the framework

conditions for students' skills acquisition for different respondent groups that involve teachers and school leaders (Fraillon et al., 2020). The underlying assumption is that the respective conditions, including the competencies and digital practices of teachers, play a decisive role in the development of students' CIL and should thus be studied. As a result, the *ICILS 2018* allows the examination of teachers' personal and work-related conditions for the use of ICT in schools.

ICILS 2018 gathered data from a total of 14 countries. In each country, a representative sample of around 150 schools was drawn. Within each school, 15 teachers were selected, leading to data from more than 26,000 teachers (Mikheeva & Meyer, 2020).² For this article, data from the following countries are considered: Chile, Denmark, Germany, the Republic of Korea, and the USA. The analysis sample contains more than 10,000 teachers. Further characteristics of the participants can be found in Table 2.

Table 2. Description of the sample.

	Chile	Denmark	Germany	Republic of Korea	USA
Sample size	N = 1682	N = 1108	N = 2303	N = 2122	N = 3174
Sex/Gender					
Female	60.64%	59.12%	61.09%	66.07%	67.77%
Male	39.36%	40.88%	38.91%	33.93%	32.23%
Age in Years (Mean)	40.02	45.32	45.33	43.99	42.66

The data were collected in 2018, using both paper-based and digital questionnaires. Further information about the study can be obtained from the International Report of the *ICILS 2018* study (Fraillon et al., 2020) and the *ICILS 2018* User Guide (Mikheeva & Meyer, 2020).

7.2. Instruments and Operationalization

As part of the teacher questionnaire, the *ICILS 2018* collected information on teachers' background, educational practices, attitudes, and self-assessed competencies, as well as their participation in digitalization-related PD which is in the center of the present article. The participation in digitalization-related PD is operationalized by five individual items. These will be considered individually for the analyses with respect to research question 1. In order to examine the relationship between the participation in digitalization-related PD and the variables associated with successful PD, as outlined in research question 2, a latent variable will be formed from the five items. The teacher quality will be measured by the positive views on using ICT in teaching and learning. To assess teaching behavior, the frequency of teachers' use of ICT in the classroom and the emphasis on promoting ICT-related skills among students are considered. All three outcome variables are latently constructed. An overview of the constructs utilized, including the number of items, sample items, and the response scales can be found in Table 3. The table also includes reliability values based on the total sample of all five countries. The questions were all developed in English but were translated into the local language for the survey. Further information regarding the scales can be derived from the user guide of the *ICILS 2018* study (see Mikheeva & Meyer, 2020). In addition, participants' age group (younger than 25 years; 25–29 years; 30–39 years; 40–49 years; 50–59 years; and 60 years or older)³ and gender (measured in binary) were included as control variables (Mikheeva & Meyer, 2020).

Table 3. Items used in the analyses.

Construct	Items	α
Participation in structured-learning PD related to ICT	How often have you participated in any of the following professional learning activities in the past two years? 5 items, e.g., a course on how to use ICT to support personalized learning by students. 1—Not at all; 2—Once only; 3—More than once.	0.84
Positive views on using ICT in teaching and learning	To what extent do you agree or disagree with the following practices and principles in relation to the use of ICT in teaching and learning? Using ICT at school: 6 items, e.g., improves academic performance of students. 1—Strongly disagree; 2—Disagree; 3—Agree; 4—Strongly Agree.	0.86
Use of ICT for teaching practices in class	How often do you use ICT in the following practices when teaching your reference class? 8 items, e.g., the provision of feedback to students on their work. 1—I never use ICT with this practice; 2—I sometimes use ICT with this practice; 3—I often use ICT with this practice; 4—I always use ICT with this practice.	0.92
Emphasis on developing students CIL	In your teaching the reference class in this school year, how much emphasis have you given to developing the following ICT-based capabilities in your students? 9 items, e.g., to access information efficiently. 1—No emphasis; 2—Little emphasis; 3—Some emphasis; 4—Strong emphasis.	0.93

Sources: Mikheeva and Meyer (2020, pp. 257, 259, 262–263); analyses by the authors.

7.3. Methodical Approach

To answer the first research question, the items on participation in digitalization-related professional development in the five selected countries were examined using the IEA International Database Analyzer (IDB Analyzer) version 5.0.23, taking into account the teacher weight (Tieck & Meinck, 2020). Mean differences between the countries were analyzed using *t*-tests. Due to the weighted data, the results are presented with standard errors to reflect the uncertainty of the parameters. For the processing of ICILS data, this is the recommended standard procedure (Mikheeva & Meyer, 2020).

To answer the second research question, linear structural equation models (SEM) were calculated for both the international sample and each country separately using the Mplus version 8.10 (Muthén & Muthén, 1998–2017). This procedure can be used to test theoretically based multiple directional relationships between latent constructs (Hair et al., 2021). Goodness-of-fit indices commonly used in research were used to assess the predictive power of the structural equation model: Root Mean Square Error of Approximation (RMSEA), Standardized Root Mean Square Residual (SRMR), Comparative Fit Index (CFI), and the Tucker–Lewis Index (TLI) (Hair et al., 2021; Xia & Yang, 2019). The values were interpreted in accordance with the cutoff values established by Kline (2010) and Brown (2015). According to these criteria, a model demonstrates a good fit to the data if both the CFI and the TLI assume values ≥ 0.95 , the RMSEA values ≤ 0.06 , and the SRMR values ≤ 0.08 . It

is asserted that an acceptable model fit can be achieved with values up to $CFI/TLI \geq 0.90$ and $RMSEA/SRMR \leq 0.08$.

The SEM analyses are performed using the robust maximum likelihood estimation method (MLR), so that the violation of the normal distribution is taken into account in the calculation of standard errors and test statistics (Li, 2016). All the values were estimated using the full information maximum likelihood (FIML) method (Grimm & Wagner, 2020), whereby all cases with no valid values were removed. Weighted teacher data were used for all analyses. The variable TOTWGTT from the ICILS datasets was used for this purpose (Tieck & Meinck, 2020).

8. Results

8.1. Participation in Digitalization-Related Professional Development

The results of the descriptive analysis to answer research question 1 about participation in five different content areas of digitalization-related PD for teachers for the five countries considered in this article are presented in Table 4. First, it can be seen that participation in all types of digitalization-related PD is higher in the USA than in the other four countries. In Chile, Denmark, Germany, and Korea, the largest proportions of teachers did not participate in any PD in any of the five content areas. In each case, the proportion ranges from 45.14 percent to the highest level of non-participation among German teachers at 95.41 percent for courses on the use of ICT for students with special needs or specific learning difficulties. In this area, Chile, Korea, and the USA also have the highest non-participation rates across all fields. In addition, in Chile, Denmark, Germany, and Korea, more teachers in all five areas of digitalization-related PD have only participated once in a training course in the respective area instead of several in the same area (with the exception of Germany with regard to a course on the use of ICT for students with special needs or specific learning difficulties). In the USA, on the other hand, this applies to only two areas: a course on the use of ICT for students with special needs or specific learning difficulties and a course on how to use ICT to support personalized learning by students. In the other three areas, the proportion of teachers who have taken more than one such course is even higher than the proportion of teachers who have not taken any such course.

Table 4. Descriptive results on teachers' participation in digitalization-related professional development in the five countries (percentages and standard errors).

	Participation of Teachers	Chile	Denmark	Germany	Republic of Korea	USA
A course on ICT applications (e.g., word processing, presentations, internet use, spreadsheets, databases)	Never	51.86 (2.09)	72.06 (1.93)	73.85 (1.74)	56.08 (2.48)	37.43 (1.42)
	Once	27.11 (1.75)	16.80 (1.75)	17.76 (1.22)	30.34 (1.99)	25.10 (1.13)
	More than once	21.02 (1.84)	11.14 (1.06)	8.40 (1.31)	13.58 (0.87)	37.47 (1.48)
A course or webinar on integrating ICT into teaching and learning	Never	63.60 (2.08)	66.56 (1.73)	68.53 (2.07)	50.71 (2.03)	34.93 (1.33)
	Once	23.67 (1.77)	19.33 (1.36)	22.77 (1.93)	33.46 (1.96)	26.21 (1.53)
	More than once	12.73 (1.47)	14.10 (1.31)	8.70 (0.93)	15.83 (0.85)	38.86 (1.88)

Table 4. Cont.

	Participation of Teachers	Chile	Denmark	Germany	Republic of Korea	USA
Training on subject-specific digital teaching and learning resources	Never	67.91 (1.80)	45.14 (1.89)	69.34 (1.83)	46.98 (2.67)	29.72 (1.36)
	Once	20.16 (1.56)	32.98 (1.78)	21.95 (1.71)	38.25 (2.81)	27.17 (1.32)
	More than once	11.92 (0.87)	21.88 (1.53)	8.71 (1.06)	14.77 (0.75)	43.11 (1.86)
A course on use of ICT for students with special needs or specific learning difficulties	Never	85.69 (1.16)	63.79 (2.91)	95.41 (0.86)	81.61 (1.22)	66.65 (1.56)
	Once	9.34 (0.91)	24.51 (2.24)	1.62 (0.38)	14.37 (1.11)	18.29 (1.48)
	More than once	4.97 (0.72)	11.70 (1.35)	2.97 (0.56)	4.03 (0.41)	15.06 (1.00)
A course on how to use ICT to support personalized learning by students	Never	77.39 (1.51)	71.03 (2.09)	77.75 (1.26)	70.34 (1.22)	54.28 (1.76)
	Once	14.47 (1.36)	17.28 (1.27)	14.89 (1.06)	23.00 (1.21)	24.92 (1.21)
	More than once	8.15 (1.01)	11.69 (1.66)	7.37 (0.93)	6.66 (0.60)	20.80 (1.11)

For a further comparison of PD participation, Table 5 contains mean values and the results of *t*-tests, indicating significant differences between the countries. Across all ICT-related topics of PD considered, the USA has the highest mean values and Germany the lowest. For two of the five distinguished topics, Denmark exhibits the second lowest level of participation. For the other three topics, the second lowest mean is found in Chile. The majority of tested mean differences are significant.

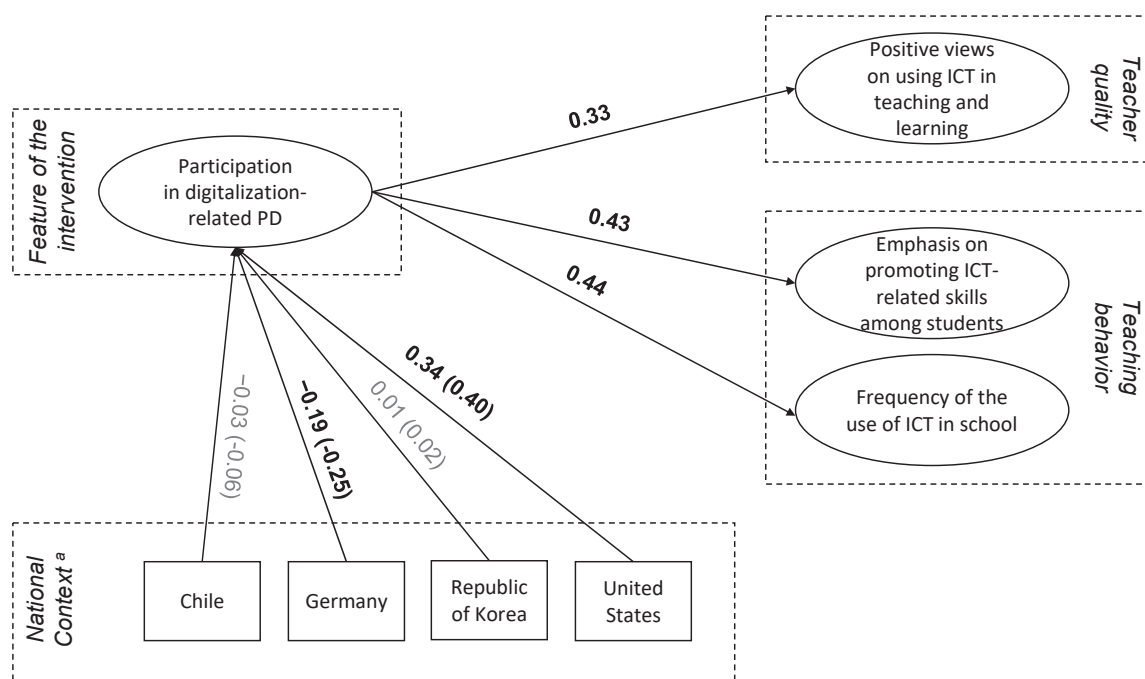
Table 5. Means (standard errors) and results of *t*-tests.

Variable	(a) Chile	(b) Denmark	(c) Germany	(d) Republic of Korea	(e) USA
A course on ICT applications	1.69 ^{b,c,d,e} (0.04)	1.39 ^{a,d,e} (0.03)	1.35 ^{a,d,e} (0.03)	1.58 ^{a,b,c,e} (0.03)	2.00 ^{a,b,c,d} (0.03)
A course or webinar on integrating ICT into teaching and learning	1.49 ^{c,d,e} (0.03)	1.48 ^{d,e} (0.03)	1.4 ^{a,d,e} (0.03)	1.65 ^{a,b,c,e} (0.02)	2.04 ^{a,b,c,d} (0.03)
Training on subject-specific digital teaching and learning resources	1.44 ^{b,d,e} (0.02)	1.77 ^{a,c,d,e} (0.03)	1.39 ^{b,d,e} (0.03)	1.68 ^{a,b,c,e} (0.02)	2.13 ^{a,b,c,d} (0.03)
A course on use of ICT for students with special needs or specific learning difficulties	1.19 ^{b,c,e} (0.02)	1.48 ^{a,c,d} (0.04)	1.08 ^{a,b,d,e} (0.01)	1.22 ^{b,c,e} (0.01)	1.48 ^{a,c,d} (0.02)
A course on how to use ICT to support personalized learning by students	1.31 ^{b,d,e} (0.02)	1.41 ^{a,c,e} (0.04)	1.3 ^{b,d,e} (0.02)	1.36 ^{a,c,e} (0.01)	1.67 ^{a,b,c,d} (0.03)

Remarks: Superscript letters indicate statistically significant differences between countries ($p < 0.05$); for example, the mean value of the USA for the participation in courses on ICT applications ($M = 2.00$) differs significantly from the mean values of (a) Chile ($t(3483.35) = 6.20, p = 0.00$), (b) Denmark ($t(3241.97) = 14.38, p = 0.00$), (c) Germany ($t(5286.37) = 15.32, p = 0.00$), and (d) the Republic of Korea ($t(5061.95) = 9.90, p = 0.00$). Response scale: 1 = never; 2 = once; 3 = more than once.

8.2. Impact of Teachers' Participation in Digitalization-Related Professional Development

To answer the second research question, the relationship between teachers' participation in digitalization-related PD and the outcomes associated with successful PD is examined both jointly and separately for the five countries using structural equation modeling. The results are presented in Figures 3 and 4. As displayed in the figures, the model fits of all six models calculated are acceptable.



^a The reference category for the national context is Denmark. Standardized values are displayed; unstandardized values are inserted in parenthesis for the dummy variables. N=10,416; RMSEA=0.03; CFI=0.93; TLI=0.92; SRMR=0.06.

Bold: $p \leq 0.001$, gray – not significant. Participation in PD: $R^2 = 0.25$; positive views on ICT: $R^2 = 0.11$; emphasis on promoting students' ICT skills: $R^2 = 0.27$; frequency of ICT-use: $R^2 = 0.28$.

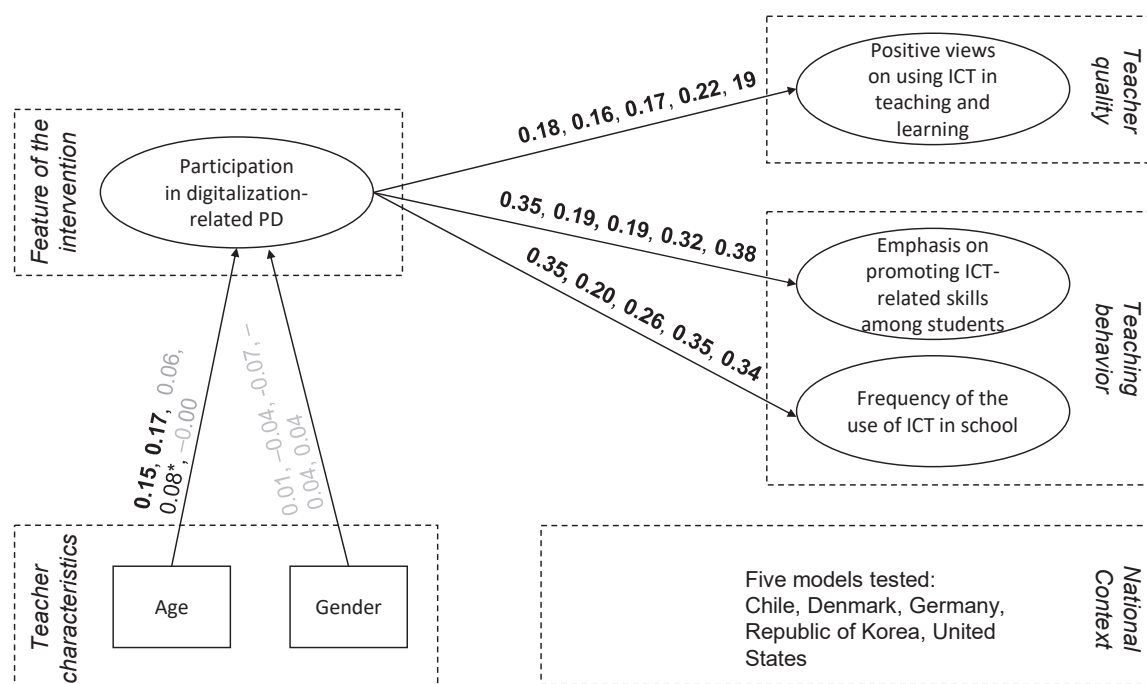
Figure 3. The relationship between PD and teacher-related outcomes in five countries: results of SEM.

The results of the joint model displayed in Figure 3 show that teachers' participation in digitalization-related PD has significant positive relationships with their positive views on using ICT in teaching and learning ($\beta = 0.33$), as well as with their emphasis on promoting students' ICT-related skills in class ($\beta = 0.43$) and their use of ICT for teaching practices in class ($\beta = 0.44$) in the international sample. The model includes the dummy-coded countries as predictors of participation in PD. Denmark was chosen as a reference category as it is the country that exhibited the highest level of ICT-related skills among students in the *ICILS 2018* sample (Fraillon et al., 2020). The results show that Germany has a significantly lower participation ($\beta = -0.19$; $b = -0.25$), and the USA has a significantly higher participation in PD ($\beta = 0.34$; $b = 0.40$) compared to Denmark. The effects of Chile and Korea were not significant.

Overall, the model excluding the control variables age and gender was able to explain 25 percent of the variance in the participation in digitalization-related PD, 11 percent of the variance in teachers' positive views on using ICT in teaching and learning, 27 percent of the variance in the emphasis on promoting ICT-related skills among students, and 28 percent of the variance in teacher' use of ICT in school.

The examination of the separate models for the five countries (see Figure 4) corroborates the significant relationships between the constructs that have been presented in the previous paragraphs. Across all countries considered, PD is connected to teachers'

ICT-related views and teaching behavior. The identified relationships are stronger in Chile, Korea, and the USA than in Denmark and Germany. Furthermore, these models included control variables. They show that, in terms of individual characteristics, teacher gender is not significantly associated with participation in digitalization-related PD in any of the countries. However, a significant positive association was found for age in Chile, Denmark, and Korea. Older teachers in these three countries are more likely to participate in such PD than younger teachers. The R^2 values for the latent outcomes are notably lower in the separate models than in the joint model.



n: 1682, 1108, 2303, 2122, 3174; RMSEA: 0.04, 0.04, 0.03, 0.04, 0.03; CFI: 0.92, 0.92, 0.91, 0.92, 0.93; TLI: 0.91, 0.91, 0.90, 0.91, 0.93; SRMR: 0.05, 0.05, 0.05, 0.05, 0.04; Bold: $p \leq 0.001$, * $p \leq 0.05$, gray – not significant. Participation in PD: $R^2 = 0.02, 0.03, 0.01, 0.01, 0.00$; positive views on ICT: $R^2 = 0.03, 0.03, 0.03, 0.05, 0.04$; emphasis on promoting students' ICT skills: $R^2 = 0.12, 0.04, 0.04, 0.11, 0.15$; frequency of ICT-use: $R^2 = 0.12, 0.04, 0.07, 0.12, 0.12$. Order of consecutive coefficients by country: Chile, Denmark, Germany, Republic of Korea, United States.

Figure 4. The relationship between PD and teacher-related outcomes: results of separate SEM including control variables.

9. Discussion

9.1. Summary and Classification of the Results

The aim of this article was to make an international comparison of teacher participation in digitalization-related PD and to explore the relationship between the participation and different aspects of teachers' ICT-related views and teaching behavior in five countries. To this end, both descriptive and inferential analyses were conducted using representative samples of teachers in Chile, Denmark, Germany, Korea, and the USA from the *ICILS 2018*.

The results of the analyses conducted in relation to research question 1 indicate that the different framework conditions (separate subject or integration into all subjects, support for participation in digitalization-related PD, IT resources, and priority of facilitating ICT-use) in the countries considered in this article do not seem to have the expected predictive power on teachers' participation in digitalization-related PD. The analyses show that teachers in the United States participate in digitalization-related PD significantly more frequently than teachers in the other four countries, as would be expected given the framework conditions presented in chapter 4. On the other hand, the participation in Denmark is not as high as would be expected, leading to hypothesis H1a, "Denmark and the

United States have the highest participation rates within the sample", being confirmed regarding the USA but refuted regarding Denmark. Germany was expected to display moderate participation rates in comparison to the other four countries. However, the data show that this country has significantly lower means than the rest of the sample. With this result, hypothesis H1b, *"Korea and Germany have moderate participation rates"*, must also be partly refuted. In Chile, the participation rate in ICT-related PD was higher than expected when compared to the rest of the sample. This finding leads to the rejection of hypothesis H1c, *"Chile exhibits the lowest participation rate within the sample"*. It can be concluded that the overall participation rates regarding digitalization-related PD are contingent on a variety of infrastructural, contextual, and personal characteristics and can consequently not be explained solely in terms of the aspects considered in this article. Further longitudinal research should incorporate measures of teachers' ICT-related views and competencies prior to their participation in PD to assess their needs. For example, teachers in Denmark, the country with the highest CIL among students, may already possess strong digital competencies, which could result in a reduced need for specialized PD in this area.

As presented in chapter 4, findings from *TALIS 2018* (OECD, 2019) and *GEW 2008* (GEW Deutschland, 2009) demonstrate that, in an international comparison, the USA, Korea, and Germany exhibit remarkably high rates of teacher participation in professional development, with participation rates ranging from 98 to 99 percent within a one-year period. The comparison of these data to the findings of the present study suggests that teaching with and about ICT is perceived as a less pressing priority in the Republic of Korea and, to a greater extent, in Germany.

In the second part of this article, structural equation modeling led to the conclusion that participation in digitalization-related PD is positively related to teachers' views on using ICT in teaching and learning (H2a), their emphasis on promoting ICT-related skills among students (H2b), and their frequency of using ICT in the classroom (H2c), as assumed on the basis of previous study results (Drossel & Eickelmann, 2017; Thurm, 2020). These findings are also in line with the theoretical model by Merchie et al. (2018). Thus, the respective hypotheses are considered confirmed. As the relationships were significant in all five countries studied, hypothesis H2d, *"The anticipated relationships are also observed when each country is analyzed individually"*, is also confirmed. The identified relationships were of moderate strength across all countries, although they were weaker in the European countries Germany and Denmark. This indicates that the effectiveness of PD is influenced by the respective context. Future research should explore these variations in greater depth, which could help identify the specific conditions that promote successful PD and facilitate mutual learning in an international context. The current findings represent an important first step, expanding on existing research that primarily focuses on individual local PD initiatives. They also contribute to a broader, international understanding of the relationship between digitization-related PD and various aspects of ICT-related attitudes and classroom practices among teachers. Furthermore, the small and mostly non-significant influence of age and gender on teachers' participation in digitalization-related PD shown in other studies (OECD, 2009; Richter et al., 2010) was also demonstrated in the present analysis in all five countries, indicating only minor national differences. None of the countries displayed significant gender effects regarding participation in digitalization-related PD. However, the analysis revealed a higher probability of older teachers participating when compared to younger teachers in Chile, Denmark, and Korea. For only two of the countries, which also have the highest (USA) and lowest (Germany) participation rates within the sample, no age-effects could be observed. This variation could be attributed to a number of reasons, which should be investigated in future studies, taking into account the different needs, obligations, and incentives to participate in PD. Especially the voluntary nature of

participation and the individual prerequisites of teachers with regard to digital attitudes and competencies should be considered.

9.2. Implications, Limitations, and Prospects

The present study offers valuable insights into the participation of teachers in digitalization-related PD and its relationship with their views on the use of ICT in the classroom, as well as their approach to teaching with and about ICT in different countries. However, the formulation of directional relationships within the SEM in this article is based solely on the framework of Merchie et al. (2018), as the cross-sectional data from the ICILS 2018 study do not permit the testing of causal assumptions. It is recommended that future studies examine the effectiveness of PD internationally on the basis of longitudinal data in a pre-post design. In this context, it would also be relevant to test for reciprocal effects between participation in PD and its outcomes. Furthermore, better information on the framework (e.g., format and duration) and quality of the teacher PD courses attended would be relevant to better identify which features of PD actually contribute to success. Unfortunately, it was not possible to implement this approach in this article, as this information is not included in *ICILS 2018*. A comprehensive test of the effectiveness of PD should furthermore include ICT-related student results, which is not possible in the *ICILS 2018* research design because teachers and students are a separate target population and there is no guarantee that they have interacted at all in teaching-learning contexts. It should also be noted here that the data used from *ICILS 2018* are based on teachers' self-assessments and therefore represent their subjective perceptions.

A replication of the present study would also be valuable because the data used are from 2018. In recent years, the COVID-19 pandemic in particular has led to a number of developments in schools, but also in the continuing education sector, especially with regard to the topic of ICT, which need to be explored in more detail. In 2018, only a small proportion of teachers in four of the countries surveyed had even participated in digitalization-related PD, so it would be interesting to investigate whether this has changed as a result of the developments. For this purpose, it would also be useful to repeat this analysis with the data from the next *ICILS* cycle in 2023.

Despite the limitations, some practical implications can be drawn from the findings. In all five countries studied, participation in digitalization-related PD was shown to have a positive effect on the implementation of ICT in the classroom. Accordingly, participation in such PD should be further promoted in the countries, and the offer should be expanded. Especially in the area of digitalization, where there is constant progress and innovation, teachers need further support even after their initial training. They should be offered lifelong learning in the field of ICT through PD so that they can adapt their teaching to current circumstances and best prepare students for life in an increasingly digitalized world. Due to the different levels of knowledge of teachers, attention should be paid to providing a diverse range of digitalization-related PD. There should be both beginners' courses for teachers who have not had ICT in their education, as well as a range of courses at more advanced levels. There should also be a wide range of content to give teachers every opportunity to use ICT, including with specific groups of students, such as those with special needs, a topic on which very few teachers in this article have perceived PD. Finally, in order to create an adequate supply of digitalization-related PD, the specific needs in each country need to be further identified in order to achieve a good match between supply and demand.

However, in order for teachers not only to learn about the use of ICT in the classroom during their professional practice, but also to be able to integrate it at the beginning of their career, it seems sensible to (more strongly) integrate the use of ICT in teacher education.

In this way, the importance of using ICT can be made clear to them at an early stage. It is hoped that this will motivate teachers more to use ICT and to participate in further PD. This would be particularly desirable as participation was still rather low in the countries surveyed in 2018.

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

Notes

- ¹ Teachers’ digital competence is an evolving concept, described in different terms and encompassing a variety of different skills and competencies (Ilomäki et al., 2016). In an overview of conceptualizations in the literature, Skantz-Åberg et al. (2022) find seven recurring aspects of teachers’ professional digital competence: technological competence, content knowledge, attitudes to technology use, pedagogical competence, cultural awareness, critical approach, and professional engagement.
- ² The participating countries of *ICILS 2018* were Chile, Denmark, Finland, France, Germany, Italy, Kazakhstan, Korea, Luxembourg, Portugal, the United States, and Uruguay. On top, Moscow (Russian Federation) and North Rhine-Westphalia (Germany) were benchmarking participants who only took part in the study with individual regions, cities, or provinces of a country. North Rhine-Westphalia is unique in that it participated both as a region of Germany and as part of the German sample with an oversampling of 80 additional schools (Fraillon et al., 2020). The sample criteria for the teacher survey was a weighted overall participation rate of 75 percent, which in Denmark, Kazakhstan, France, and the USA was only met after the incorporation of replacement schools (Fraillon et al., 2020).
- ³ In an international comparison, only the simple index *T_AGE* from *ICILS 2018* is available. The approximate age of teachers is used here. The following simple recoding was performed: less than 25 = 23; 25–29 = 27; 30–39 = 35; 40–49 = 45; 50–59 = 55; and 60 or over = 63 (Mikheeva & Meyer, 2020, p. 64).

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Article

Rethinking Professional Development: Development and Evaluation of an Evidence-Based Online PD Course on the Effective Use of Technology in the Classroom

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Abstract: Technology-enhanced teaching (TET) is most effective when integrated meaningfully into classroom settings. Teachers require technological pedagogical knowledge (TPK) to achieve this integration. This study details the development and evaluation of an online professional development (OPD) course aimed at enhancing teachers' TPK for the effective use of technology in science and language subjects. The course was created to rethink OPD, i.e., to overcome known shortcomings of OPD design consciously. It was based on the Interactive–Constructive–Active–Passive (ICAP) framework, which promotes interactive and constructive learning activities. Thus, the OPD course incorporated text-based and video-based interactive learning modules (*learning nuggets*), discussions about staged video vignettes showing classroom situations with *conventional* vs. *good* use of technology by the teacher, professional learning communities, and practical teaching trials with group reflections. The evaluation study of this OPD followed a pre–post design involving 76 in-service teachers. Participants completed surveys and a test of their ability to apply ICAP knowledge to teaching situations before and after the OPD. The evaluation revealed that teachers perceived the course as beneficial, though no statistically significant improvement in applied ICAP knowledge was observed. These findings highlight opportunities and challenges in designing and measuring effective OPDs that support the meaningful integration of technology into classroom practice.

Keywords: online professional development; ICAP; in-service teacher training; pre–post design; teachers' technological pedagogical knowledge

1. Introduction

The effectiveness of technology-enhanced teaching (TET) depends on how technology is integrated into teaching–learning settings (Fütterer et al., 2022, 2023a; Petko et al., 2017). Effective technology integration in the classroom requires teachers to have technology-related professional knowledge (e.g., technological pedagogical knowledge [TPK]; Mishra & Koehler, 2006; see also Fütterer et al., 2023b; Runge et al., 2023). Professional development (PD; Darling-Hammond et al., 2017) and online PD (OPD; Morina et al., 2025) have proven to be effective ways of promoting teachers' TPK and increasing teachers' effective use of technology (e.g., Fütterer et al., 2024d; Hillmayr et al., 2020; Runge et al., 2023), but their effectiveness is associated with PD quality (Fütterer et al., 2024b). Numerous recommendations for quality characteristics of (online) PD exist, such as opportunities for

collaboration and exchange (e.g., Darling-Hammond et al., 2017; Meyer et al., 2023; Quinn et al., 2019), which should be considered when developing an (O)PD¹. However, there are remarkable differences between how (O)PDs are usually designed and implemented in practice and how they should be designed and implemented according to empirical evidence to achieve sustainable changes in teaching practice, and these differences are rarely reported in detail (for a few exceptions, see Fütterer et al., 2024d, 2025; Hauk et al., 2023)—especially not with suggestions on how to overcome these differences. To this end, we provide an in-depth insight into the systematic, interdisciplinary (Pedagogical Content Knowledge [PCK] experts, education sciences and psychology researchers, and in-service teachers) development of an OPD to train in-service teachers in effectively integrating technology in teaching related to two disciplines (natural sciences and languages). The OPD lasted approximately 18 h, across several weeks (see Table A1), took OPD quality characteristics into account, and comprised four key components: *interactive learning modules* (learning nuggets) with self-assessments, discussions on *staged video vignettes* to elaborate scenarios of technology integration by comparing conventional and good classroom practice, *professional learning communities*, and *practical teaching trials* with subsequent group reflections. The theoretical basis for the effective use of technology in the classroom in OPD is the Interactive–Constructive–Active–Passive (ICAP) framework (Chi & Wylie, 2014). We provide insight into our approach and experiences with exemplary challenges that OPD providers face. These include, among others, the length of an OPD, the balance between research-based and practical relevance, and dropout rates in non-mandatory OPD courses. Finally, we provide insight into the evaluation results (i.e., both the perceived and tested effectiveness of the OPD).

2. Theoretical Background

2.1. Teacher Professional Development to Promote Teachers' Competence in Providing High-Quality Technology-Enhanced Teaching

Technology-enhanced teaching (TET) must be of high quality to be effective for students (Fütterer et al., 2022, 2023a). In the context of high-quality teaching, the emphasis lies not on *whether* technology is used but on *how* it enhances learning outcomes through thoughtful application. Thus, teachers must be prepared to orchestrate the use of technology in a meaningful way (Scheiter, 2021), that is, have digital competence. Teacher competence generally refers to the integrated knowledge, skills, self-regulation, work-related motivation, and beliefs that enable teachers to support student learning effectively (Blömeke et al., 2015; Kunter et al., 2013). Regarding TET, the key area of *teaching and learning* of the DigCompEdu framework (European Commission. Joint Research Centre, 2017) describes aspects of teachers' digital competence and highlights teachers' knowledge of how technology, pedagogy, and content interact while creating effective digital learning environments. Therefore, TPK (Mishra & Koehler, 2006) is a helpful cognitive resource and a prerequisite for teachers to act competently. For instance, teachers must be able to distinguish between instances when digital technology is merely replacing an analog medium that is not more effective for students' learning and those when the potential of technology is being used to support students' learning.

Professional development (PD; Darling-Hammond et al., 2017) and online PD (OPD; Dede et al., 2009, 2016) have proven promising interventions to support teachers (Morina et al., 2025), especially when promoting high-quality TET (Fütterer et al., 2025; Hillmayr et al., 2020; Runge et al., 2023). For OPDs to be effective, they should be of high quality (e.g., providing opportunities for teachers for interactive learning; Fütterer et al., 2024b; Meyer et al., 2023; Quinn et al., 2019) and “practice what they preach” regarding TET and TEL (technology-enhanced learning). However, the specific design elements of OPDs aimed

at improving TET and their theoretical foundation have rarely been made transparent. Moreover, previous OPD courses show shortcomings, especially when promoting teachers to provide effective TEL.

2.2. Examples of Shortcomings of (Online) Professional Development

Globally, (O)PD courses are often characterized by pitfalls and challenges such as (a) short duration, (b) passive participation, or (c) a lack of focus on the systematic development of competencies (Borko et al., 2010; Darling-Hammond et al., 2017; Hill, 2009; Krille, 2020).

(a) Internationally, there is a wide variation in the duration of (O)PD, which is not necessarily an indicator of effective (O)PD (e.g., in terms of student performance; Sims & Fletcher-Wood, 2021). However, (O)PD of longer duration offers more opportunities for repeated practice. In particular, opportunities to implement new classroom practices help to build new and improved teaching habits (Sims & Fletcher-Wood, 2021). Ideally, effective (O)PD changes teachers' behaviors in such a way that student performance measurably improves (Sims & Fletcher-Wood, 2021), thus allowing for an evaluation of results, in line with Kirkpatrick's fourth level of training evaluation (Kirkpatrick & Kirkpatrick, 2006). Despite the well-known importance of repeated practice, in Germany, (O)PD is often delivered as a one-shot of two to eight hours (Johannmeyer & Cramer, 2021). The preference for short (O)PD formats might be due to teachers' limited time for PD (Fütterer et al., 2024a; Richter et al., 2020).

(b) In addition to one-shot formats, these short PD events are often dominated by lectures on specific topics, which in turn are accompanied by passive learning activities on the part of the participants (Ball & Cohen, 1999; Borko et al., 2010). In Germany, (inter)active learning and cooperation among teachers, as induced by professional learning communities (PLCs; Doğan & Adams, 2018), rarely play a role in (O)PD courses (Lipowsky & Rzejak, 2021). Whereas there are many topics for which short (O)PD is suitable, they are less likely to result in the sustained development of complex competencies (Cramer et al., 2019), such as high-quality TET. This is because such (O)PDs often do not provide enough opportunities to (iteratively) connect new theoretical knowledge with practical applications and to reflect on one's newly gained classroom experiences (Rzejak & Lipowsky, 2020) in groups or small PLCs. These processes promote (co)constructively developed new perspectives and feedback. Therefore, participants in such (O)PD may be less likely to change their teaching by implementing the (O)PD practices.

(c) Regarding the promotion of TPK, many (O)PDs have a strong focus on TK (i.e., tool usage). For instance, Fabian et al. (2024) found that TPACK-based interventions tend to target TK (80%). The preference for instructions on how to use specific tools serves the expectation that (O)PD practices are directly applicable by teachers in the classroom (Johannmeyer & Cramer, 2021). However, a lack of an overarching concept on how to apply (O)PD practices to one's practice (Bonnes et al., 2022) and low implementation rates after (O)PD participation suggest that is not the case: teachers may know about effective teaching but do not implement (O)PD practices into their own practice unless they are given opportunities to practice and receive feedback (Sims et al., 2023). In Germany, this is illustrated by the Landesmedienzentren (LMZ), the federal state's media centers, which focus on offering TK and tool-usage-related (O)PD (Stricker & Heitz, 2020). Notably, the LMZ typically offer unconnected short sessions, each introducing different tools that exemplify the tendency for PD to focus on TK without overarching concepts.

2.3. The Theoretical Foundation of a New Online Professional Development Course

We have systematically designed a theoretically sound and evidence-based OPD to overcome the abovementioned pitfalls. The primary purpose of the OPD was to promote

teachers' TPK based on the ICAP framework as part of their digital competence. This knowledge base should enable teachers to assess the effectiveness of technology in the classroom in terms of student learning.

The technological pedagogical content knowledge (TPACK) model postulates that teachers need to possess technological knowledge (TK) in addition to content knowledge (CK) and pedagogical knowledge (PK; Mishra & Koehler, 2006; see Figure 1). TK covers, for instance, knowledge about technical functions and how to operate digital media. One facet of knowledge that is important for implementing high-quality TET and that results from the interaction of CK and PK is TPK, the domain-independent “understanding of how teaching and learning can be changed when particular technologies are used in particular ways” (Koehler & Mishra, 2009, p. 65). Therefore, our OPD aimed to promote teachers' general knowledge of using digital media to make teaching more effective for student learning (i.e., TPK).

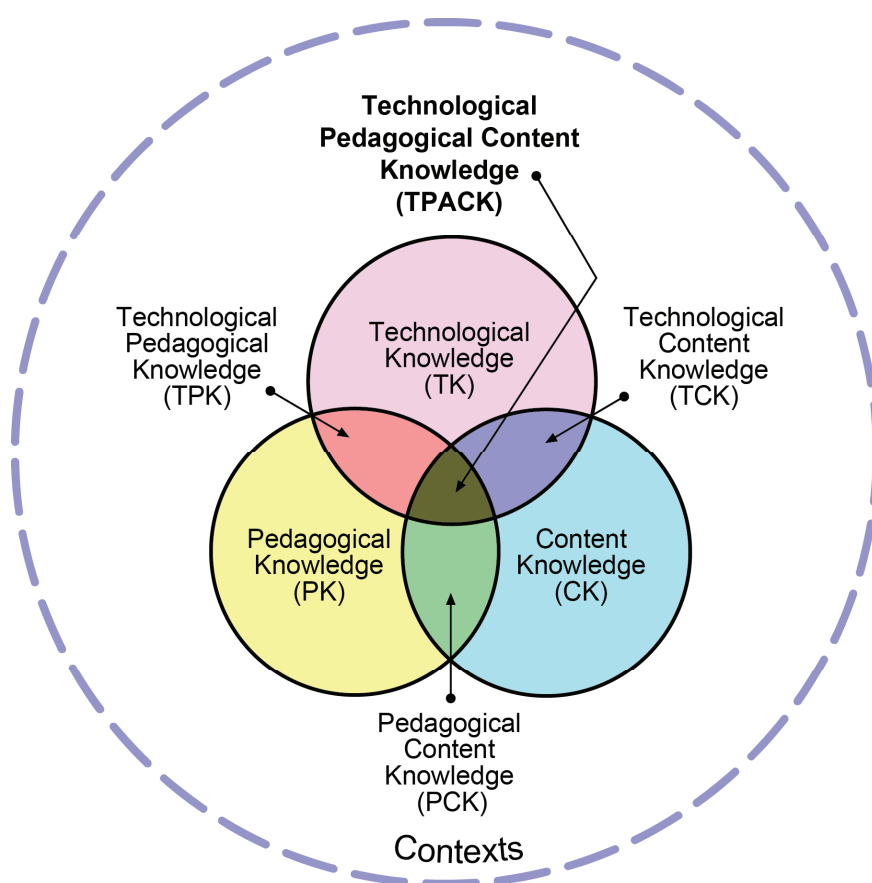


Figure 1. Technological Pedagogical Content Knowledge (TPACK) framework. Note: reproduced with permission of the publisher, © 2012 by tpack.org.

Regarding TPK, we focused on aspects of students' deep processing during learning. We used the ICAP framework (Chi & Wylie, 2014) to derive guidelines on enhancing teaching using technology that could be implemented in the OPD. The framework proposes a positive correlation between observable physical learning activities and cognitive engagement. The framework distinguishes four types of cognitive engagement and learning activities: *passive*, *active*, *constructive*, and *interactive*. For a representation of the modes and an overview of the framework's assumptions, see Figure 2.

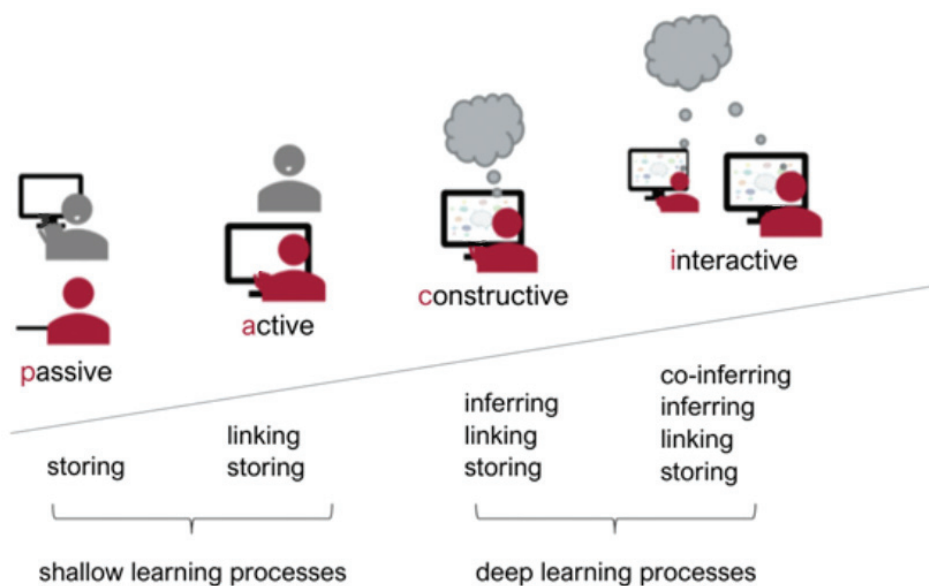


Figure 2. Assumptions of the ICAP framework regarding cognitive processes. Note: figure adapted from Sailer et al. (2024).

According to the ICAP framework, students who engage in *passive* learning activities, characterized by physical inactivity such as listening or watching without taking notes or exchanging ideas with their classmates, are assumed to exhibit minimal cognitive engagement, which is less likely to result in skill acquisition or deep learning without further active or constructive engagement. Students who engage in *active* learning activities are physically active and manipulate materials, for instance, by copying notes from the blackboard. Active students are likely more cognitively engaged compared to passive students, as they probably activate prior knowledge, which could cause new knowledge to be linked to prior knowledge, making it easier to retrieve (Chi et al., 2018). The passive and active modes are called “shallow processing strategies” (Chi et al., 2018, p. 1783), potentially allowing for information retrieval. Students who show constructive learning activities are physically active and mentally involved in generating something new, building on prior knowledge beyond the provided input, such as the learning materials (e.g., constructing a concept map; Chi et al., 2018). When students *construct* something new, they are assumed to be more likely to generate knowledge transferable to new situations. Students involved in *interactive* or co-constructive learning activities are engaged similarly to constructive students; however, their product is created through dialogue with other students, with everybody contributing equally. For instance, students could be encouraged to discuss the pros and cons of a controversial topic, which may lead to new insights and knowledge that would not be possible when learning alone. Interactive learning activities stimulate the highest cognitive engagement, producing well-connected knowledge structures. The constructive and interactive modes are called “deep processing strategies” (Chi et al., 2018, p. 1783), potentially allowing for a deeper understanding of the learning content.

In our OPD, we aimed to help teachers understand which ICAP mode is appropriate for a specific learning objective. This skill is crucial, as not every use of technology is more effective for students. For instance, digital technology can enable higher ICAP modes than analog forms, such as students watching a video on their devices and being able to individually and actively start, stop, and re-wind the video as needed instead of passively watching as the teacher presents it. Sailer et al. (2024) suggest that technology’s ability to enable a higher ICAP mode may be the most important effect of technology on teaching. However, using technology alone does not ensure a higher ICAP mode; on the contrary, it might hinder it (Fütterer et al., 2023a). If, for instance, a teacher substitutes students’ filling out a paper worksheet asking for

freely constructed answers with a digital multiple-choice quiz such as Kahoot using closed answers, then this approach is predicted to be less effective as the more cognitively engaging constructive, and generative activity is replaced with one that is merely active and requires students to click on the most likely answer option mechanically.

At the same time, we did not aim to encourage teachers to always choose the interactive mode when planning TEL. If a lower mode is enough to achieve a learning objective (e.g., recall instead of inference making), then an activity designed for a higher mode may waste resources. Consequently, we wanted the teachers to understand the link between ICAP modes and specific learning objectives. Moreover, we aimed to provide opportunities for teachers within the OPD to read about, watch, or experience (co-)constructive activities with technologies in classrooms, as teachers may fail to imagine what technology-supported deep learning activities could look like (e.g., co-construction by using collaborative writing tools).

2.4. The Key Elements of the OPD Concept

Our OPD is based on four key complementary elements, which we identified based on evidence of increasing the chances of transferring the OPD content to teachers' classroom practice. These four elements are (1) encouraging active learning by offering short, *interactive learning nuggets* with self-assessments, (2) using *staged lesson video vignettes* of classroom practice encouraging critical discussion, (3) implementing PLCs, and (4) including *practical applications of OPD content to one's teaching practice* in the form of developing, revising, implementing, and reflecting on an actual lesson. For a graphical overview of the four key complementary elements of the OPD, see Figure 3. Based on the experiences of our pilot study, we offered our four key elements in a compact synchronous three-day structure of two short and one day-long sessions (see Table A1) spaced two weeks apart each to also allow participants to focus on and engage with our OPD course content asynchronously, reducing absences. We offered two variants of this structure, one focusing on natural sciences and one focusing on modern foreign languages, which differed in the content of the learning nuggets and the staged video vignettes, which will be detailed in the following sections.

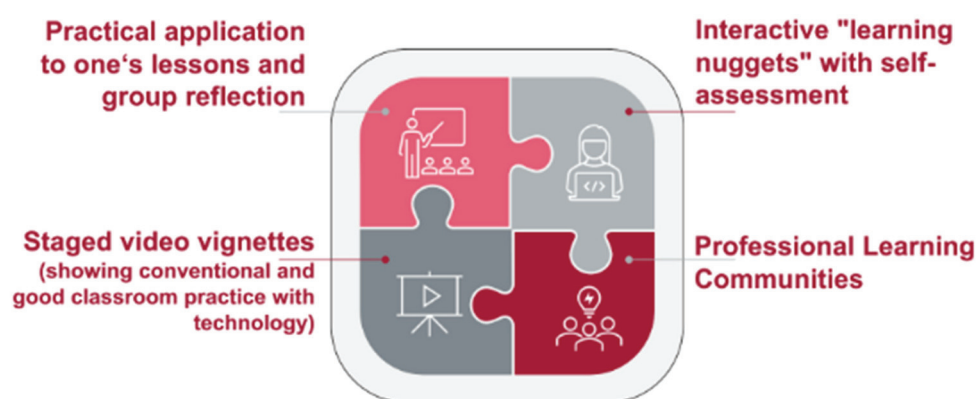


Figure 3. Four key complementary design elements of the OPD.

2.5. Interactive Learning Nuggets

Learning nuggets have emerged as a promising approach in OPD, particularly for addressing the need for flexible and active engagement in professional learning (e.g., Fütterer et al., 2024d, 2025). Learning nuggets are designed to reduce cognitive load (Corbeil et al., 2021) while increasing flexibility, allowing participants to asynchronously engage with content in manageable sessions that accommodate their busy schedules (Kohnke et al., 2024). Moreover, microlearning methods such as learning nuggets have been perceived as less stressful and more adaptable than traditional (O)PD formats, which often require longer

time commitments (Kohnke et al., 2024). Furthermore, the ICAP framework underscores the value of active learning, positing that deeper engagement with the material leads to more effective learning outcomes (Chi & Wylie, 2014).

Our OPD offered two sets of interactive learning nuggets that lasted just a few minutes each to encourage participants' active engagement with the learning materials, ensuring that participants could easily fit these activities into their schedules whenever they had a spare moment. These were separated into TPK-focused videos and PCK-focused interactive texts, which will be described below. Moreover, our design was underpinned by a flipped classroom approach, where theoretical content was presented asynchronously, enabling participants to prepare independently before synchronous meetings (Hew et al., 2021). This flipped classroom approach aimed to facilitate deeper engagement during live discussions and gave participants a sense of control over their learning pace. In addition, by allowing participants to choose which two of three PCK modules to complete (e.g., being able to choose if they would instead learn about top-down and bottom-up processing in listening comprehension, metacognitive strategies in listening comprehension, or differentiation in flipped classrooms), we aimed to cater to individual interests and knowledge gaps, thereby fostering personalized learning.

The learning nuggets conveyed theoretical knowledge and practically demonstrated tools and strategies that participants could use in their teaching. These included digital tools such as H5P and LearningApps and strategies for enhancing interactivity in videos and texts, thereby modeling effective digital pedagogical practices. Participants were allowed to experience effective digital teaching strategies from a learner's perspective, which could help them appreciate the potential benefits of these methods for their students. We implemented learning nuggets in two formats: *interactive videos* and *interactive texts*. The interactive videos were created with H5P; see Figure 4 for one example. These videos included features such as automated feedback on multiple choice questions integrated directly into the videos, allowing participants to self-assess their understanding of the content, as depicted in Figure 4. The topics of these videos included concepts relevant to TPK, such as the ICAP framework and gamification. For teachers who were less familiar with digital tools, we also provided baseline TK content, such as creating and using collaborative documents using Cryptpad.fr, Google Docs, and Word 365. These videos were kept short to ensure they could be watched during free time.

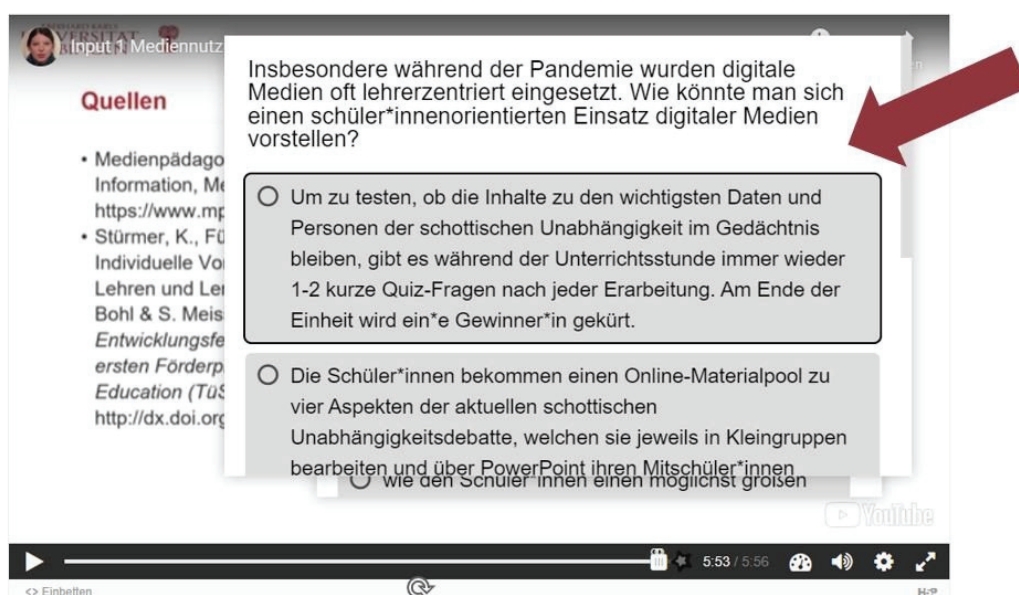


Figure 4. Example of self-assessment questions at the end of a TPK-focused learning nugget (in-teractive video format). Note. Translation: Especially during the pandemic, digital media were

often used in a teacher-centered way. How could you imagine a student-centered use of digital media?—To test whether the content on the most important dates and people concerning Scottish Independence is remembered, there are 1–2 short quiz questions after each activity—A winner is chosen at the end of the unit. The students receive an online pool of material on four aspects of the current Scottish Independence debate, which they work on in small groups and present their results to their classmates via PowerPoint. (Answer options 3 and 4 not depicted.)

The interactive texts were developed using LearningApp.org (<https://learningapps.org/>); for an example, see Figure 5. These texts were tailored to the specific content focus of participants, depending on whether they were natural science or language teachers. As Fabian et al. (2024) suggest, TPACK has a domain-specific character, and domain-specific TET is still understudied, yet we can assume that TPK is closely connected to TCK. Thus, we developed two separate sets of interactive texts. For instance, one activity required science-focused participants to sort arguments for and against using virtual simulations versus real experiments, which provided insights into the benefits and limitations of using these methods in science education. This activity introduced new instructional strategies and encouraged participants to engage deeply with the content, enhancing their understanding through active participation.

Baustein 1: Top-down- und Bottom-up-processing Als erledigt kennzeichnen ✕

Themas zuvor verstanden und verinnerlicht wurden.

Dies bedeutet, dass der Aktivierung der bottom-up und top-down-Verarbeitungsprozesse während der pre-listening-Phase eine große Bedeutung für das Gelingen der gesamten Stunde zukommt — und zukommen sollte. Wird Hörverstehen nur als Selbstzweck abgefragt — ist aber für den Erfolg der weiteren Stunde jenseits der Frage, wie viele Antworten man auf einem Arbeitsblatt abhaken kann, nicht relevant — fragen sich SuS berechtigterweise, wozu sie es beherrschen sollen. Die Bedeutung der Motivation für das Hörverstehen ist nicht zu unterschätzen.

Nun sind Sie dran!

1) **Ordnen** Sie bitte die folgenden Praxisbeispiele und Anweisungen, die im Unterricht erfolgen könnten, entsprechend zu, je nach dem ob diese darauf abzielen, das **bottom-up oder top-down**-Verständnis zu fördern, beziehungsweise ob dieses beeinträchtigt wird.

☺ Welche von diesen würden Sie gerne häufiger nutzen?

Bottom-up processing

Top-down processing

SuS sollten viele verschiedene Dialekte und Akzente kennenlernen, so dass sie Wörter auch erkennen, wenn diese anders ausgesprochen werden.

Figure 5. Example of interactive elements in a PCK-focused learning nugget (interactive text format). Note. Translation: This means that the activation of bottom-up and top-down processing during

the pre-listening phase is—and should be—of great importance for the lesson’s success. If listening comprehension is only tested for its own sake—but is not relevant for the success of the rest of the lesson beyond the question of how many answers can be ticked off on a worksheet—students will justifiably ask themselves why they should master it. The importance of motivation for listening comprehension should not be underestimated. Now, it is your turn! (1) Please categorize the following practical examples and instructions that could be given in class according to whether they aim to promote or negatively affect bottom-up or top-down comprehension. 😊 Which of these would you like to use more often? Students should learn many different dialects and accents to recognize words when they are spoken.

The learning nuggets were designed to include self-assessment components to encourage participants’ engagement and reflection. For instance, a video on the ICAP framework ended with questions prompting participants to recall key concepts, apply them to practical situations, and reflect on their relevance to their teaching practice. All videos included this type of self-assessment to address three dimensions: understanding the content, applying it practically, and reflecting on its application to one’s context. This design should have encouraged knowledge transfer from theory to practice, helping participants bridge the gap between what they learned and how they could implement it in their classrooms.

2.6. Staged Video Vignettes

Video vignettes are designed to bring the intricate classroom experience into the (O)PD setting (Oser et al., 2010). Video vignettes approximate the classroom reality by removing the immediate demands of showing actions in complex classroom situations, allowing teachers to analyze and discuss teaching (Brovelli et al., 2013). Such analytical engagement can promote analytical competence (Goeze et al., 2010; Zottmann et al., 2012) and may encourage teachers to consider the perspectives of their students (Goeze et al., 2014). Expert teachers can effectively understand the perspectives of both teachers and learners (Berliner & Carter, 1989; Carter et al., 1988), and they have a multi-layered understanding of problems and solutions in the classroom (Hogan et al., 2003). Therefore, video vignettes have been highlighted as valuable tools in (O)PD, allowing teachers to connect theoretical foundations to teaching practice (Fütterer et al., 2024c; Goeze et al., 2014; Krammer, 2014; Stürmer et al., 2013).

The case studies in our OPD included examples of *good practice* and *conventional practice* to provide diverse modeling opportunities. The good practice case studies served as models of effective teaching approaches, which are beneficial in teacher PD (Sims & Fletcher-Wood, 2021). In contrast, the conventional practice examples allowed participants to learn from common mistakes in a proxy situation. Research suggests that the combination of relatively good and common examples (i.e., showing the contrast) is more effective for learners than merely providing only good examples (Booth et al., 2013).

To this end, we created four staged-lesson video vignettes for our OPD, two focusing on language and two on natural science content, with each focus having two variants: conventional practice and good practice. Each of the four videos was about ten minutes long and was carefully scripted to illustrate fundamental principles taught in our OPD. The conventional practice and the good practice videos did not differ in their teaching objective. The scripts were developed in collaboration with experienced teachers and experts regarding the content knowledge to ensure authenticity and quality in both video versions. These videos were filmed with real students and teachers, capturing a lesson in a condensed timeframe. This was achieved through targeted editing, for example, showing only the beginning and end of a group work phase. The language-focused lesson featured a listening comprehension activity in English for grade 7, whereas the natural science-

focused lesson showed 12th-grade students working with a biology simulation. These topics were selected because of their broad applicability across subjects and age groups. The videos were designed to offer various discussion options related to the OPD content (e.g., demonstrating the use of digital tools in different ICAP modes, showcasing flipped classroom implementations, and highlighting gamification and virtual simulations). In Figures 6 and 7, the teacher and the students create a collaborative mind map in TaskCards, illustrating one way to encourage co-construction and collaboration with digital tools. We were mindful of the potential perception that academic content might be too theoretical or detached from classroom realities (Frank et al., 2023). Therefore, we ensured that the situations shown in the videos were practical and feasible for teachers. We explored the videos with various participants, including university students and in-service teachers, to ecologically validate our vignettes. Most participants agreed that the use of digital media in the classroom represented in the good-practice videos was indeed “good”, which was crucial for achieving our modeling goals. Feedback on the conventional practice videos was mixed, particularly regarding authenticity, as participants noted that teachers would not use that many digital tools in a single lesson. This outcome was expected, as we intentionally compromised on the authenticity of the conventional practice videos for didactic reasons: We aimed to avoid suggesting that simply increasing the number of digital tools used would lead to better teaching outcomes. Instead, we aimed to guide participants’ attention to how the same tools could be used to either enhance or limit student engagement (Fütterer et al., 2022). This approach addressed the misconception that digital media automatically improve teaching effectiveness. Studies support that the quality of digital media use, rather than its quantity, influences the effectiveness of lessons (Fütterer et al., 2022), with positive effects being more likely when digital tools promote higher ICAP modes and include additional scaffolding (Fütterer et al., 2023a; Sailer et al., 2024; Wekerle & Kollar, 2022).

For instance, in one scene from the conventional practice natural sciences video, the teacher presents a virtual simulation on a smart board and then quizzes the students afterward (i.e., passive ICAP mode). In the good practice variant, students interact directly with the simulation on their own devices while answering quiz questions that prompt them to engage actively with specific simulation elements (i.e., active ICAP mode). This difference illustrates how the ICAP framework could be applied practically, with the second variant demonstrating a potentially more engaging and cognitively demanding approach.



Figure 6. First screenshot from a staged video vignette. Note: students are adding comments to a TaskCards wall on their tablets.

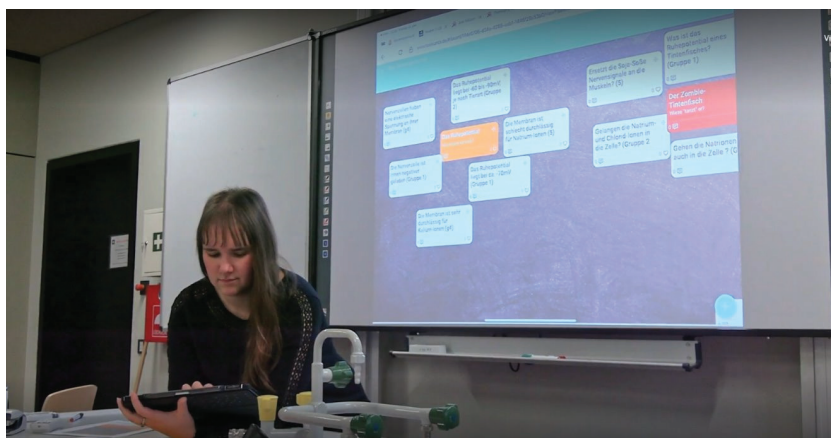


Figure 7. Second screenshot from a staged video vignette. Note: the teacher presents and critically examines students' comments on her tablet.

We deliberately avoided labeling any example as *bad* or *best* practice and instead encouraged participants to critically discuss potential strengths and weaknesses in both examples. This approach was intended to prevent the suggestion of a one-size-fits-all solution of high-quality TET. For instance, not all schools can provide every student with a digital device connected to the internet. If teachers were led to believe that this scenario represented the ideal approach, they might feel discouraged from finding the best possible solution for their unique context.

2.7. Professional Learning Communities

Based on the concept of *communities of practice* introduced by Lave and Wenger (2009), PLCs are conceptualized as a specific type of teacher collaboration, frequently defined as “a group of educators motivated by the same vision to improve student success” who are working “collaboratively through a reflective process” (Çopur & Demirel, 2022, p. 301). They are associated with improved teacher practice and increased student achievement (Çopur & Demirel, 2022; Doğan & Adams, 2018). For instance, PLCs offer the opportunity to receive feedback and social support, which are important elements of effective (O)PD (Sims & Fletcher-Wood, 2021).

In our OPD, we introduced PLCs as a regular opportunity for teachers to meet in set groups of three or four—each of the three synchronous meetings allowed for PLCs to meet online. We decided to allow participants to be sorted according to a preference for a given subject and age group (e.g., teaching English in grades 5 to 7). This was based on our team’s previous OPD experience, where participants indicated that they did not find it fruitful to share ideas if their counterparts did not share their subject or primarily taught a different age group (Fütterer et al., 2025). After assigning participants to groups, we first encouraged them to strengthen their social bonds and get to know one another, for example, by discussing ice-breaker questions. We provided participants with guiding questions to ensure productive collaboration during each PLC activity, in which all participants are involved. For example, participants discussed the video vignettes. They added their conclusion about what they considered improved in the good-practice video compared to the conventional-practice video to a TaskCard. We encouraged the teachers to exchange and negotiate different perspectives. We hoped to reduce OPD dropout and to encourage lasting cooperation even after our OPD ended by establishing PCLs that met on Zoom. We allowed participants to select the subject and age range they would like to focus on in the pre-test and created groups of 3–4 participants accordingly.

2.8. Practical Application of OPD Content to One's Teaching Practice

By definition, it is generally assumed that (O)PD is effective if associated with changes in teaching practice (Desimone, 2009). However, (O)PD often does not result in a changed teaching practice (Osman & Warner, 2020). Regarding promoting TPK, Chi et al. (2018) found that OPD participants often misunderstand the ICAP framework. For instance, OPD participants created supposedly constructive tasks requiring students to re-organize provided knowledge (i.e., an active learning activity) or supposedly interactive activities in which students did not exchange ideas.

Many studies have shown that practicing and receiving feedback, self-monitoring, and action planning are important elements of effective (O)PD (Sims et al., 2023). These elements are all facilitated by creating, implementing, and discussing a lesson plan. Therefore, in our OPD, participants were asked to develop, revise, implement, and reflect on lesson plans. Teachers could choose a topic that needed to include at least one new practice they had gained from the OPD. We provided a blank spreadsheet with a row for each ICAP mode, along with other planning categories, to ensure participants would consider the ICAP framework when planning their lesson. Time to brainstorm ideas within the PLCs, to work on lesson plans, and to ask for help from the team members was included in the synchronous sessions.

2.9. Research Questions and Hypotheses

Given the previous descriptions and an evidence-based foundation, we assumed that the OPD should be particularly effective and ideally well-received by participants due to its engaging nature, leading to positive evaluations and low dropout. Consequently, in addition to providing a detailed description of the theoretical foundation and implementation of design elements of the OPD, the second aim of this article was to provide insights into the effectiveness of this OPD. Therefore, we addressed four research questions (RQs) and formulated the following hypotheses (Hs):

(RQ1) How did the participating teachers perceive the online professional development course?

We did not formulate a hypothesis in this case but looked at the data exploratively.

(RQ2) How did the teachers' ability to apply ICAP knowledge to teaching situations change during the online professional development course?

As the OPD is based on empirically proven theories of successful teacher learning and ICAP knowledge was taught and applied in the OPD, we expected teachers' ability to apply ICAP knowledge to teaching situations to develop positively (i.e., increase) from before to after the OPD course (H1).

(RQ3) How were teachers' cognitive, motivational, and demographic characteristics related to teachers' ability to apply ICAP knowledge to teaching situations after the online professional development course?

We did not formulate a hypothesis in this case but looked at the data exploratively.

(RQ4) What characteristics of teachers predicted their dropout from the online professional development course?

Based on findings from the evaluation of OPDs (Fütterer et al., 2025), we expected that teachers with lower TK and TPK knowledge, as well as lower ability to apply ICAP knowledge to teaching situations at t_1 were more likely to drop out of the OPD compared to teachers who scored higher on these tests (H2).

3. Method

3.1. Development of the Online Professional Development Course and Procedure

We used an iterative approach of interweaving research and practice. In line with a design-based research (DBR) approach, educational and educational psychology re-

searchers, PCK experts, and in-service teachers were involved in developing, designing, and optimizing the OPD materials (e.g., video vignettes) and schedule. According to the DBR approach, in this study, we provide “rich descriptions” (Anderson & Shattuck, 2012, p. 22) of the OPD key elements and their theoretical foundation (see above), the development cycles, and the procedure and context of the OPD implementation. In addition, we provide insights into participants’ feedback after the OPD.

The OPD was conducted in two rounds to improve the OPD over different iterations (Anderson & Shattuck, 2012). Parallel materials were developed for natural sciences (e.g., Biology, Chemistry, and physics) and languages (e.g., English as a Second Language, French, and Spanish), which were offered with the same PD structure. The provision of domain-specific content is because some subjects are more similar than others (Tenorth, 2020, e.g., conducting experiments in natural science subjects), TPK and PCK being related (Fabian et al., 2024), and due to the experience in previous OPDs, in which participants expressed a wish for more domain-specific materials to connect more strongly to their subject and to be able to talk to other teachers of related subjects (Fütterer et al., 2024d, 2025).

3.2. Procedure and Implementation of the OPD

The second and third authors implemented the OPD in two rounds (the first round between January and April 2023 and the second round between June and July 2023). In the first round, the OPD was conducted on a small scale to gain insight into which OPD features the participants were already satisfied with and which features needed to be revised. In the second round, after adapting the OPD features based on the experiences of the first round (e.g., optimized efficiency of the time spent on individual OPD contents, the composition of contents), the OPD was offered via several federal states’ teacher training centers in Germany. The OPD schedule was developed to offer the participants several opportunities to transfer OPD content to their practice and to develop their digital competence incrementally. See Table A1 in the Appendix A for an overview of the OPD schedule.

Regarding the technical implementation of the OPD, we used the conference software BigBlueButton version 2.7 in the pilot study and Zoom for online video conferencing in synchronous meetings in the efficacy study. We used Moodle’s learning management system to provide the participants access to the OPD materials (e.g., worksheets). We implemented the OPD content as interactive videos with H5P and interactive texts with LearningApps. Some reflection questions were collected via Cryptpad’s survey function. The PLCs used collaborative documents in the Microsoft 365 suite (Word, PowerPoint) and made notes of their group discussions in TaskCards.

3.3. Study Design of OPD Evaluation and Data Collection Procedure

We implemented a systematic OPD evaluation, focusing on the effectiveness of the OPD at two different levels (Level 1: teacher satisfaction with the OPD; Level 2: effectiveness of the OPD at teacher level; Fütterer et al., 2024b; see also Kirkpatrick & Kirkpatrick, 2006). For this purpose, we implemented a pre–post design in which teachers were surveyed (e.g., on motivational aspects such as TEL self-efficacy) and tested (e.g., ability to apply ICAP knowledge) with an online instrument utilizing the survey software Unipark (www.unipark.com) both before (t_1) and after the OPD (t_2). The pre-test questionnaire of the first round was available from 3 January 2023 to 18 January 2023, and it took the participants around 60 min to complete. The pre-test questionnaire for the second round was available from 6 June 2023 to 18 June 2023, and it took the participants around 45 min to complete, as it was shortened compared to the first round’s version. In this study, we summarize the data sets of the two rounds. The pre-tests included questions on how valuable participants expected technology to be, perceived self-efficacy with technology

(only first round), how much cognitive activation was considered a factor in their regular lessons, and demographic questions, including age, gender, grades in their first and second state exam, as well as their roles in the school.

Additionally, we asked the participants about the technology school equipment (e.g., Wi-Fi) and participants' experiences with and motivations for participating in PDs. Furthermore, we tested participants' TPK, TK, and ability to apply ICAP knowledge to teaching situations. The post-test of the first round was performed from 22 March 2023 to 9 April 2023, and from 11 July 2023 to 27 July 2023, for the second round. The same questions as for the pre-tests were used, except for questions about participants' demographic background, school equipment, PD experience, and professional experience, which we expected to be stable between t_1 and t_2 . In addition, questions about participants' satisfaction with elements of the OPD were included.

The whole questionnaire and the corresponding scale manual can be viewed in our OSF project (see the link in the declaration section).

3.4. Sample

The sample included teachers who provided data at least at the first measurement point, resulting in 76 participants. Of the participants, 67% were female, and 50% reported working with a reduced workload. The participants had an average of 13.00 years of teaching experience ($SD = 7.72$). Regarding subject areas, 57% taught English, 22% French, 18% mathematics, 16% German, 14% chemistry, 10% physics, and 9% biology.

3.5. Instruments

Regarding research question one, we assessed teachers' perception of the OPD at t_2 . We used a scale consisting of four self-developed items to measure teachers' perception of the effectiveness of the OPD at different levels from teachers to students (e.g., "The professional development course was effective for my skills and abilities [i.e., I have more knowledge and/or higher competencies, etc. regarding the course topics than before my participation in the course]"). Teachers answered the items on a four-point response scale (1 = *not at all true* to 4 = *exactly true*). The scale showed excellent internal consistency (Cronbach's Alpha $\alpha = 0.95$). In addition, we used a scale consisting of four self-developed items to measure teachers' perception of the quality of the video vignettes used in the OPD (e.g., "The video vignettes realistically depict everyday teaching situations"). Teachers answered the items on a four-point response scale (1 = *not at all true* to 4 = *exactly true*). The scale showed good internal consistency ($\alpha = 0.74$). Finally, we used six self-developed items to assess teachers' perception of different aspects of the OPD, such as the preparation of theoretical input as video learning nuggets. Teachers answered these items on a six-point response scale (1 = *does not apply at all* to 6 = *fully applies*).

Regarding research questions two and three, we assessed teachers' ability to apply knowledge of using technology according to the ICAP framework to teaching situations at t_1 and t_2 utilizing a self-developed single-choice situational judgment test comprising twelve items (for an example item, see Figure 8). The Wright map (see Figure A1) showed a balanced difficulty distribution of the items (i.e., the items' difficulty matches the respondents' abilities, indicating that the items were neither too easy nor too hard for the sample; see also the item characteristic curves in Figure A2). We used arithmetic mean scores to represent teachers' proficiency levels and calculated difference values ($t_2 - t_1$) as the dependent variable.

Item (A)			
Ms. Schubert wants the students to be able to quickly recall the knowledge conveyed. Which approach is appropriate? Please provide your answer based on the ICAP framework by Chi and Wylie. Always opt for the lowest level of the ICAP model with which you could achieve the described teaching objective. [German: Frau Schubert möchte, dass die Schüler:innen dazu in der Lage sind, vermitteltes Wissen zügig abrufen zu können. Welches ist das passende Vorgehen? Bitte geben Sie Ihre Antwort auf Grundlage des ICAP-Rahmenmodells nach Chi and Wylie. Entscheiden Sie sich immer für die niedrigste Stufe des ICAP-Modells, mit der Sie das beschriebene Lehrziel erreichen könnten.]			
Option 1 (P)	Option 2 (A)	Option 3 (P)	Option 4 (C)
The students listen to a presentation of learning content (e.g., via PowerPoint) by the teacher. [German: Die Schüler:innen hören bei einer Präsentation zu Lerninhalten (z.B. via Powerpoint) des/der Lehrer:in zu.]	The students watch an instructional video on the learning content and take notes. [German: Die Schüler:innen schauen ein Erklärvideo zu Lerninhalten und machen sich Notizen.]	The students read different digital texts on the learning content through station-based learning. [German: Die Schüler:innen lesen mittels Stationenlernens unterschiedliche digitale Texte zu Lerninhalten.]	The students research learning content on the internet, compare different perspectives, and summarize them in their own words. [German: Die Schüler:innen recherchieren im Internet zu Lerninhalten, vergleichen unterschiedliche Perspektiven und fassen diese in eigenen Worten zusammen.]

Figure 8. Example item from the Single-Choice Situational Judgment Test. Note. A = active, P = passive, C = constructive. The correct answer is marked in bold. The bold marking and the abbreviations were not shown to the participants.

We assessed cognitive, motivational, and demographic teacher characteristics as the independent variables. That is, we tested teachers' TPK utilizing a multiple-choice test developed by Lachner et al. (2019) and teachers' knowledge of how to operate technology as part of their technological knowledge utilizing a computer-adaptive version of the test T-TK developed by Fütterer et al. (2023c). Furthermore, we assessed teachers' reported utility value of TET at t_1 using a scale of four items (e.g., "I think that technology is useful for my teaching"; Backfisch et al., 2021). The scale showed excellent internal consistency ($\alpha = 0.95$). Finally, we asked teachers to report their gender (0 = *male*, 1 = *female*), their teaching experience in years, and their workload (0 = *reduced workload*, 1 = *full workload*).

Regarding the fourth research question, we computed the dichotomous variable *drop out* (0 = *no drop out*, 1 = *drop out*), which indicates whether a teacher dropped out of the OPD. We defined dropout as the absence of available data at the second measurement point. We used all test values of the knowledge test implemented at t_1 and teachers' utility value at t_1 as independent variables.

3.6. Statistical Analyses

To answer our research questions (RQs), we performed all statistical analyses in R v4.3.2 (R Core Team, 2023).

We observed missing values on individual variables because they were not answered, and the teachers dropped out of the OPD. For instance, we observed that 1.97% of all values of items used to assess the knowledge tests (i.e., dependent variables) in this study showed missing values at t_1 and 49.89% at t_2 . Most of the missing values are due to participants' dropping out of the study (i.e., 45.10%, with most dropouts occurring directly after the pre-test questionnaire, before the actual OPD started). We applied a multiple imputation approach to address missing values (van Buuren, 2018). We generated 50 complete data sets using the *R* package mice version 3.16.0 (van Buuren & Groothuis-Oudshoorn, 2011).

To gain insights into how satisfied teachers were with the OPD (RQ1), we calculated descriptive statistics (e.g., mean, standard deviation) to estimate the distribution of responses on the rating scale. We used the imputed data for robustness checks. To test the hypothesis of positive changes in teachers' tested ability to apply ICAP knowledge to teaching situations across the OPD (H1 regarding RQ2), we implemented a paired sample *t*-test ($DS_{t_2-t_1}$ = the difference score between t_1 and t_2). We used the imputed data for robustness checks. We implemented multiple linear regression models utilizing the imputed data to explore the importance of cognitive, motivational, and demographic teacher variables for teachers' ability to apply ICAP knowledge to teaching situations at t_2 (RQ3). Finally, we implemented logistic regressions to test the hypothesis that teachers with lower technological knowledge and ability to apply ICAP knowledge to teaching situations at t_1 are more likely to drop out of the OPD than those with stronger skills (H2 regarding RQ4). We regressed the dichotomous dropout variable on teachers' TK, TPK, and ICAP test scores. We used the imputed data for robustness checks.

The analysis code is available in our OSF project (see the link in the declaration section).

4. Results

4.1. Descriptive Results of Teachers' OPD Perception

To gain insights into teachers' perceptions of the OPD (RQ1), we looked at the descriptive statistics in Table 1. Compared to the theoretical scale mean (2.5), the teachers, on average, perceived the OPD as rather effective ($M = 2.97$, $SD = 0.73$). The video learning nuggets ($M = 4.34$ compared to the scale mean of 3.5) and the digital tools used ($M = 4.32$ compared to the scale mean of 3.5), which the teachers found to be rather helpful on average, should be positively emphasized.

Table 1. Descriptive statistics of participants' perception of the online professional development.

	<i>M</i>	<i>SD</i>	<i>Median</i>	<i>min</i>	<i>max</i>
Perceived effectiveness of OPD	2.97	0.73	3	1	4
Perceived quality of video vignettes	2.67	0.67	2.67	1	4
Perceived usefulness of the video learning nuggets	4.34	1.51	5	1	6
Perceived usefulness of small "tests" at the end of the video learning nuggets	3.97	1.53	4	1	6
Perceived usefulness of the preparation of the didactic materials as quizzes	4.08	1.36	4	1	6
Evaluation of the ease of use of the Moodle learning environment	5.05	1.01	5	1	6
Perceived usefulness of preparing and revising a lesson plan	3.71	1.54	4	1	6
Perceived ease of use of the OPD's digital tools	4.32	1.42	4.50	1	6

Note: $n = 38$. The imported statistics are comparable. *M* = arithmetic mean, *SD* = standard deviation, *min* = minimum of response scale and the observed value, *max* = maximum of response scale and the observed value, OPD = online professional development.

In addition to the ratings, participants were allowed to provide general feedback on the OPD in an open-ended answer format at t_2 . Most of the participants positively highlighted the examples of digital tools they were introduced to as learners, which they could apply during the OPD in their teaching practice, the staged video vignettes, as well as lesson ideas

provided by teachers as concrete implementation scenarios, the way the theoretical models were presented (i.e., the interactive text- and video-based learning nuggets), and the PLCs activities. Criticism mainly addressed the difficulty of finding time for the extensive OPD. Few participants expressed a wish for less theory and more extensive good practice videos and implementation examples, such as fully developed spreadsheets of lesson plans in line with the well-known preference of participants to gain knowledge that can immediately be implemented. On the one hand, many participants stated that they gained specific ideas for tools to use but also kept the ICAP framework in mind as a helpful heuristic model for reflecting on and planning more purposeful technology use in their teaching practice. On the other hand, a few of them also stated that implementing (an ICAP-inspired use of) technology would be too time-consuming and sometimes impossible in their school (e.g., due to a lack of Wi-Fi in the classroom). A few example quotes (translated by the second author):

- “- Time required to do this [will be a challenge]
- My day only has 24 h, I need more time for preparation and also our equipment at school isn't ready for this (no Wi-Fi for students, no tablets . . .)
- Our Wi-Fi doesn't work reliably”

4.2. Changes in Teachers' Ability to Apply ICAP Knowledge

We looked at the difference scores regarding the changes in teachers' ability to apply ICAP knowledge to teaching situations from before to after the OPD course (RQ2). On average, we found no statistically significant or meaningful changes ($M_{t1} = 0.47$ [$SD_{t1} = 0.16$]; $M_{t2} = 0.47$ [$SD_{t2} = 0.16$]; $t(37) = 0.97$, $p = 0.337$, $d = -0.16$). These results were robust when using the imputed data and when using only data from teachers who did not drop out of the OPD. Therefore, hypothesis 1 was not confirmed.

4.3. Associations Between Teachers' Ability to Apply ICAP Knowledge and Teachers' Characteristics

Looking at the results of the multiple regression analyses of teachers' ability to apply ICAP knowledge at t_2 on teachers' cognitive, motivational, and demographic characteristics at t_1 (RQ3; see Table 2), we found only a statistically significant regression (i.e., slope) for teachers' ability to apply ICAP knowledge at t_1 . All other statistics—besides the intercept—were not statistically significant. These results were robust when using only data from the teachers who did not drop out of the OPD.

Table 2. Regression analysis statistics of ICAP knowledge at the second measurement point based on teacher characteristics from the first measurement point.

	<i>b/b*</i>	<i>SE</i>	<i>p</i>
Intercept	0.26/−0.15	0.346	0.676
ICAP	0.41/0.46	0.133	0.001
Gender	0.01/0.08	0.326	0.802
Workload	0.03/0.18	0.319	0.573
Teaching Experience	0.00/0.01	0.134	0.954
Utility Value	0.02/0.07	0.133	0.622
Technological Knowledge	−0.04/−0.04	0.131	0.746
Technological Pedagogical Knowledge	−0.01/−0.03	0.135	0.827

Note. $R^2 = 0.08$, $F(6,31) = 0.43$, $p = 0.855$. *SE* = standard error. *b** = are xy-standardized coefficients using the *scale()* function in R. *SE* and *p* values refer to the analyses with standardized coefficients.

4.4. Prediction of Teachers' OPD Dropout

We defined OPD dropout as the absence of available data at the second measurement point. Thirty-one (40%) teachers dropped out of the OPD between the first and second measurement points, with the most dropout directly after the pre-test questionnaire—even before the actual OPD started—and directly after the OPD—even before the post-test questionnaire was provided. Regarding the fourth research question, about the associations between teachers' prior knowledge and ability and their OPD dropout, we found—against our expectations—no statistically significant associations. Therefore, hypothesis 2 was also not confirmed.

5. Discussion

5.1. Main Findings

This study detailed the development and evaluation of an OPD course to enhance teachers' TPK for the effective use of technology in natural science and language subjects. Because there are remarkable differences between how (O)PDs are usually designed and implemented in practice and how they should be designed and implemented according to empirical evidence to achieve sustainable changes in teaching practice, we wanted to rethink OPD course design, i.e., we wanted to overcome some of its known shortcomings deliberately.

To this end, we (1) successfully implemented an OPD course design that lasted over 18 hours across 4 weeks, thus overcoming the pitfall of short *one-shots* that do not allow teachers to implement new practices into their teaching practice to try out and subsequently reflect on new and improved teaching options that may lead to better teaching habits (Sims & Fletcher-Wood, 2021) as a genuine part of the OPD.

(2) To overcome passive learning and to reduce dropout, the OPD was based on the ICAP framework and PLCs, which promote interactive and constructive learning activities. Thus, our OPD course incorporated four key elements: (2a) text-based and video-based interactive learning modules (i.e., learning nuggets regarding TPK- and PCK-relevant knowledge) for teachers' self-directed learning with self-assessments, (2b) discussions about staged video vignettes showing natural science or language classroom situations with conventional vs. good use of technology by the teacher, (2c) sharing opinions and experiences in PLCs throughout the OPD, i.e., with a constant small group of colleagues who have the same subject, student body, and improvement aim in common, and (2d) practical teaching trials in one's classroom with subsequent group reflections as an integral part of the OPD course.

We successfully developed two subject-specific versions of this OPD (i.e., for natural science and languages, each featuring different materials [video vignettes, learning nuggets, digital tools, lesson ideas by teachers as concrete implementation scenarios, etc.]), as previous OPDs have shown that a lack of specificity in this regard can lead to criticism from teachers and increased dropout rates (Fütterer et al., 2025). In this study, we also wanted to provide evidence of this OPD's effectiveness (RQ 1–4). First, we found that teachers perceived the OPD positively in general, stating, for instance, that they experienced the OPD as effective. Secondly, we could not confirm this positive perception regarding teachers' tested ability to apply ICAP knowledge to teaching situations. Thirdly, we could not identify any correlations between teacher characteristics and their changes in knowledge of how to use technology according to the ICAP framework, and finally, cognitive entry requirements were not associated with teachers dropping out of the OPD.

5.2. Limitations and Future Research

We could not demonstrate that our approach improved teachers' tested ability to apply ICAP knowledge to teaching situations. However, when asked for feedback in an open-ended format (RQ 1), it was striking that three out of four elements of the OPD that we had conceived and implemented as *key elements* to overcome known shortcomings of (O)PD were also considered particularly valuable and worth retaining by the participants: more than 70% of all self-written answers mentioned either (a) the text-based and video-based interactive learning modules (i.e., learning nuggets regarding TPK and PCK relevant knowledge), (b) the staged video vignettes and/or (c) the shared experiences in PLCs throughout the OPD as effective and worthwhile to retain.

Here are the first four answers to our open feedback question (translated by the second author), highlighting the PLCs as a particularly positive element that should be retained:

- “- Exchanges in small groups, best practice examples”;
- “- Exchange of ideas”;
- “- Quiz formats that can be reused”;
- “- Introduction of few but good and easy-to-use digital tools, a lot of time spent in small groups”.

This suggests that our innovative elements were nevertheless considered particularly valuable to participants. Regarding RQs 2 and 3, we consider it a strength of this study that self-reported learning was obtained, and performance tests were also used. We assessed teachers' knowledge of using technology according to the ICAP framework at t_1 and t_2 utilizing a self-developed single-choice situational judgment test comprising twelve items. The arithmetic mean scores represented the teachers' proficiency levels. We hypothesized a significant knowledge gain, but H1 could not be confirmed. There were no correlations between teachers' cognitive, motivational, or demographic characteristics and their (changes in) ability to apply ICAP knowledge to teaching situations. We see two possible explanations for these results.

The first explanation could be a *creaming effect*: the pre-test results show unusually high positive views of TET, with participants rating the use of technology in the classroom at an average of 3.67 on a four-point scale. Most participants had taken part in other TET-PDs the previous year. This suggests that the participants who began and continued the OPD were most likely more experienced in thinking about and using digital media in the classroom. This might be why we saw no statistically significant improvement in the ICAP situational judgment test, as the participants were already performing better than expected (i.e., highly motivated and experienced teachers were overrepresented). The creaming effect becomes even more pronounced in (O)PD courses where higher-performing teachers continue participating, whereas lower-performing teachers drop out. Therefore, future research should explore strategies to recruit a more diverse participant pool, including teachers with varying experience levels, digital competence, and interest in TET. Moreover, future research should explore strategies to retain teachers with little previous knowledge or interest in TET in (O)PD (e.g., self-regulation strategies such as implementation intentions).

The second explanation could involve measurement challenges in the psychometric quality of the ICAP situational judgment test that need to be overcome and the fit between this test and the OPD program. Challenges in the psychometric quality of the ICAP situational judgment test are indicated by our ongoing IRT-based validation studies and by feedback from two participants (e.g., “I had difficulty choosing answers because too little background information was given to visualize the situation.”). When asked in an open-ended format about the primary practices from the OPD they wanted to use later in their practice, the ICAP framework was most often named (together with specific digital tools) as a helpful heuristic that altered their perception of classroom practice and

planning. We interpret this as a strong indicator that the ICAP framework is at least perceived as a perception-altering heuristic framework. However, we could not detect improvements in the ICAP situational judgment test we administered in 2023. Moreover, whereas the OPD focused on fostering teachers' practical understanding of integrating technology into higher ICAP modes (constructive and interactive), the test relied on abstract scenarios that may not have fully aligned with the nuanced, practice-oriented training provided. This potential misalignment between the instrument and the OPD content might explain the absence of statistically significant effects, as the test may not have adequately captured the applied and context-sensitive skills emphasized in the OPD. Therefore, further research should focus on refining and validating tools to assess knowledge application and situational judgment in teaching contexts, and future studies could benefit from developing or adapting instruments to better reflect the specific competencies promoted by the training program. In addition, complementary measures, such as the qualitative analysis of lesson plans or classroom observations, could provide richer insights. For example, we would have expected participants to include digital activities in a higher ICAP mode after revisions of lesson plans. Lesson plans would have been essential to judge better whether teachers could transfer their knowledge to a potential practical application in their teaching practice. However, although we collected some lesson plans, we did not receive enough to conduct an in-depth evaluation. Based on participants' lively discussions within their PLCs and notes on their experiences written on TaskCards during breakout room phases, we assume this is not due to participants' inability to implement changes in their teaching. Instead, we suspect participants may feel uncomfortable with their teaching being scrutinized, as teachers in the German system work independently. At the same time, since watching a colleague teaching is rare and usually performed only in situations where the judgment can impact a teacher's career, such as during "teaching exams" ("Lehrproben") conducted as part of their teacher training ("Referendariat"), participants may have experienced uncomfortable associations with the tasks we asked of them. Participants' feedback to our pre- and post-test questionnaires similarly reported teachers being uncomfortable, feeling "like a student being tested". Besides a lack of time or opportunity, this may also be the reason why the fourth key element of our OPD, i.e., creating, implementing, and discussing a lesson plan, was not as valued by the participants as the other three; see above.

Regarding RQ4, we expected that teachers with lower TK and TPK and the ability to apply ICAP knowledge to teaching situations at t_1 were more likely to drop out of the OPD compared to teachers with stronger skills, but this was not the case. The PLCs could have made a difference compared to previous studies: the social cohesion effects and the exchanges in PLC might have a compensating influence, especially on those who can benefit more from the shared knowledge and experiences in these small group discussions. The PLCs were highly appreciated in the freeform feedback, as this comment illustrates: "I will try to maintain the contacts I have been able to make, as I believe that personal, professional development thrives on exchange". Future research should explore how group composition, interaction quality, and social cohesion influence participation and engagement in OPDs. Moreover, whereas the dropout rate of 41% between completing the pre-test questionnaire at t_1 ($n = 76$) and t_2 ($n = 45$) may suggest low satisfaction with the OPD, this was not the case: measured by participation in the OPD itself, the dropout rate was only 10% (from 70 to 63 participants). Thus, those who chose to participate were mainly retained as participants. Hence, most of the participants dropped out of the pre-test and post-test questionnaires rather than the OPD. Thus, for future OPDs, it will be essential to ensure the brevity of the questionnaires and to frame them positively, emphasizing their importance for effective teacher OPD.

Finally, before we state the concluding implications regarding specific OPD features, future research should aim to overcome the limitations of our research design. Whereas this study focused on immediate outcomes, the long-term impact of the OPD on teaching practices and student learning remains unclear. Longitudinal studies should examine whether the knowledge and abilities gained during the OPD translate into sustained changes in classroom practices and improved student outcomes over time. In addition, we would like to acknowledge that our current research design does not allow us to isolate the specific effects of individual elements of the OPD on teachers' skills, knowledge, or beliefs. Therefore, in general, future research should incorporate a more robust evaluation design (i.e., conducting experimental variations of the OPD design in randomized controlled trials, such as including or excluding specific components, to determine their unique impacts on outcomes) and a more detailed formative evaluation framework, including systematically collecting data at multiple points during the intervention and learning analytics. This will allow researchers to analyze teachers' interactions with specific OPD components (e.g., video vignettes, PLC discussions, or learning nuggets) to understand their contributions better.

5.3. Concluding Implications for Professional Development

Alongside the general remarks regarding the limitations of this study, we would like to make four recommendations.

First, we recommend a structured, evidence-based design of OPDs. The design of our OPD demonstrates the importance of a structured and evidence-based approach in PD, especially for promoting TET. Integrating theoretical frameworks such as the ICAP framework and evidence-based strategies (e.g., PLCs and staged video vignettes) can address known shortcomings of typical (O)PD formats.

Second, we recommend a focus on practical relevance and flexibility. Participants appreciated elements that balanced theory and practice, such as learning nuggets and staged video vignettes. Future OPDs should maintain this balance while ensuring flexibility in content delivery to accommodate teachers' busy schedules. This flexibility can mitigate time constraints, frequently cited as a barrier to participation. To foster sustainable growth in teachers' instructional practice, future (O)PD offerings should be adaptive. Adaptive means that an (O)PD course is more intentionally tailored to teachers' interests and prior knowledge, systematically adjusting content and activities to meet their unique needs better.

Third, we recommend establishing PLCs. The strong positive reception of PLCs underscores their role in fostering collaboration, reflection, and shared learning. Encouraging PLCs in PD programs may help sustain motivation, reduce dropout rates, and build social cohesion among participants. PLCs may also create opportunities for mutual support, especially for teachers with less prior knowledge or confidence in TET.

Finally, we recommend domain-specific content. Providing domain-specific materials (e.g., tailored video vignettes and lesson ideas) can enhance relevance and engagement for participants. Future OPDs should consider customizing content to address the specific needs of teachers in different subjects or educational levels.

6. Conclusions

Overall, the high OPD participant satisfaction in this first evaluation study, especially with its key elements, is a promising starting point for rethinking what OPD for teachers in Germany can look like. Now that the concept has proven to be well-received independent of topical focus, future iterations may enhance the acceptance of research and performance measurements among teachers, improve the psychometric quality of the ICAP situational judgment test, and better evaluate the classroom impact of the OPD. Together with incorpo-

rating control conditions and longitudinal measures to assess the intervention's sustained effects and real-world application of the skills acquired, these gaps highlight important avenues for future research.

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Appendix A

Table A1. Schedule of the online professional development course.

Date	Time	Content
5–11 June 2023	About 45 min	Pre-test
13 June 2023	14:00–17:00 3 h	Synchronous kick-off meeting: • First guided PLC meeting • Brainstorming of first ideas for a lesson plan
14 to 26 June 2023	About 2.5 h	Asynchronous self-study—Phase 1: • “Learning nuggets”: Interactive videos on TPK • “Learning nuggets”: Interactive texts on PCK • Video vignette “Conventional Practice”
27 June 2023	9:00–16:00 6 h (+1 h break)	Synchronous intermediate meeting: • Video vignette “Good Practice” • Second guided PLC meeting • Reflection on self-study—Phase 1 • Discussion of video vignettes • Guided trying of new digital tools • Revision of lesson plan
28 June to 10 July 2023	About 2.5 h	Asynchronous self-study—Phase 2: • Finalizing and implementing a lesson plan in one's classroom • Reflection on the implemented lesson
11 July 2023	14:00–17:00 3 h	Synchronous final meeting: • Final PLC meeting • Collective reflection on lessons held/planned • Post-test

Note. Synchronous meetings are highlighted in grey. All other sessions were self-organized by the participants.

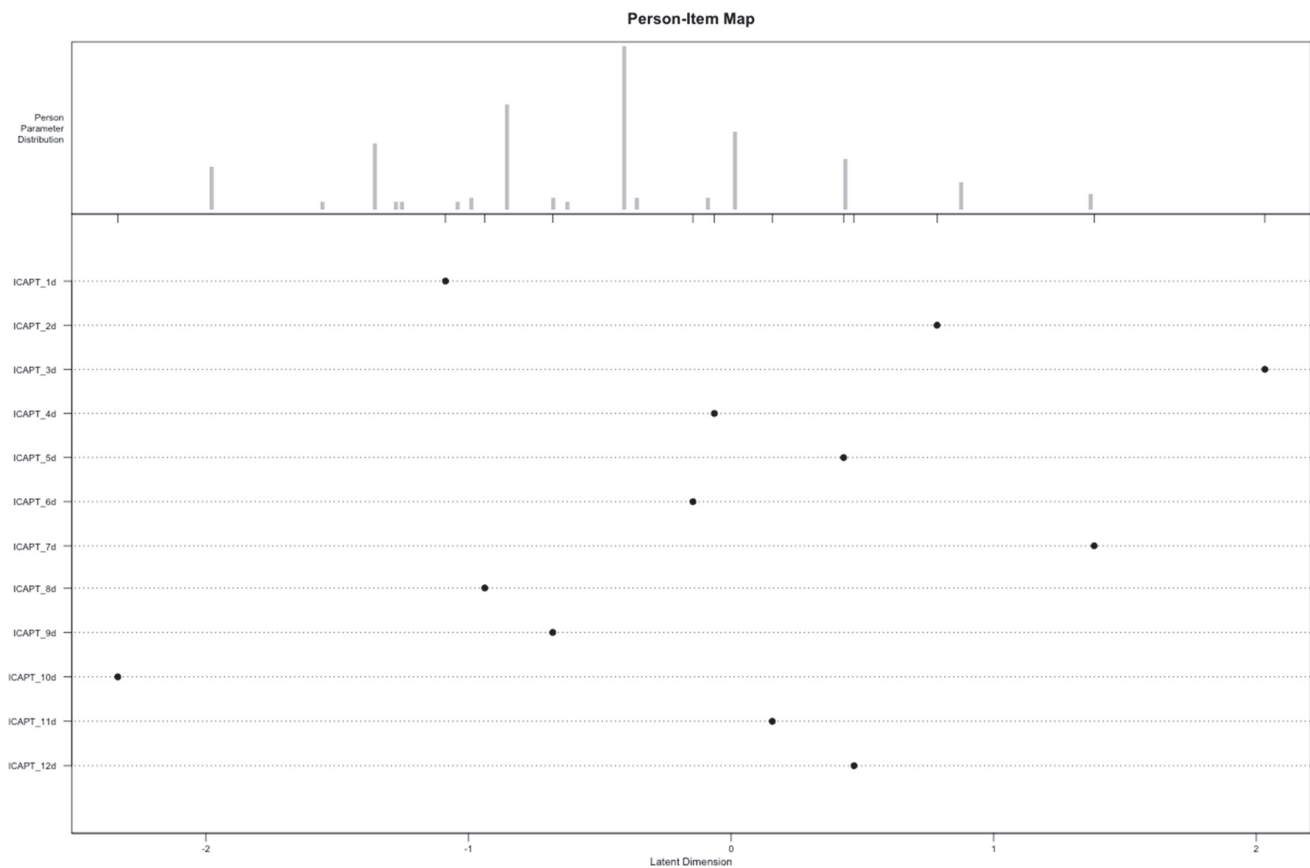


Figure A1. Wright map of the twelve items of the Single-Choice Situational Judgment Test. Note: the relationship between respondents' abilities (i.e., test-takers' abilities) and the difficulties of test items is based on a validation study involving $N = 219$ teachers.

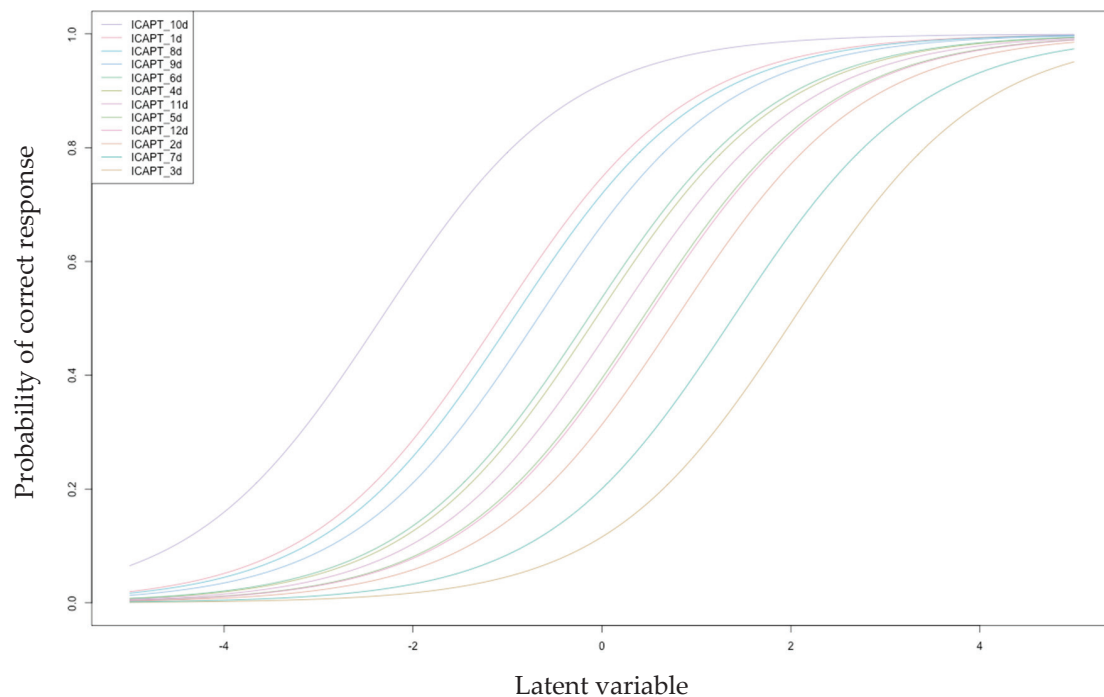


Figure A2. Item characteristic curves (ICCs) of the twelve items of the Single-Choice Situational Judgment Test. Note: the probability of a correct response to the twelve test items across varying levels of the latent variable (i.e., ability to apply knowledge of using technology according to the ICAP framework to teaching situations) is based on a validation study involving $N = 219$ teachers.

Notes

- ¹ (O)PD refers to both online (O) and face-to-face professional development (PD).

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