Modeling, Measuring and Fostering (Pre-Service) Teachers' Professional Knowledge to Integrate Technologies in Mathematics Education

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Summary

Mathematics plays a pivotal role in our rapidly changing world as it drives technological progress, facilitates scientific breakthroughs, and cultivates critical thinking necessary for addressing complex global challenges. Acquiring mathematical knowledge is therefore considered crucial in educational policy. In this context, digital technologies hold the potentials to support students in gaining a profound understanding of mathematics. For these potentials to unfold, however, technologies must be integrated effectively in the classroom by the teacher. Against this background, teachers' professional knowledge is a regarded as a crucial pre-requisite for implementing technologies in a way that supports students' conceptual understanding of mathematics. This professional knowledge of teachers is prominently subsumed under the term *Technological Pedagogical Content Knowledge* (i.e., TPCK), a knowledge component which extends beyond other knowledge components such as Pedagogical Content Knowledge (i.e., PCK) and Technological Knowledge (i.e., TK). Despite its relevance for education and beyond, however, little is known about the precise nature of mathematics-specific TPCK which is likely a result of the predominant use of self-reports in respective studies which have shown to induce validity issues. Also, the lack of reliable test-based instruments to assess mathematics-specific TPCK impedes the investigation of the relationship between TPCK and other knowledge components, leaving the theoretical underpinnings of TPCK unclear. Additionally, insights into how to effectively prepare (pre-service) teachers to teach with technologies in mathematics are limited as self-reported data only provides distal proxy for competence growth.

Against this background, the present dissertation's overarching goal was to provide a comprehensive investigation into the nature of mathematics-specific TPCK with a specific focus on how such knowledge could be assessed in an objective way, and how it could be fostered within mathematics-specific short-term interventions. To address these objectives, I conducted a total of three studies. In the first study, I extended beyond mathematics to various

subject domains and conducted a comprehensive systematic review of prior TPCK interventions based on 166 primary studies. The aim of this study was to discern whether TPCK has predominantly been conceptualized from a pedagogical, technological, or subject-specific perspective. Moreover, within a subsequent meta-analysis, I investigated the effectiveness of TPCK-interventions. In contrast to prior meta-analyses, I included only studies in this meta-analysis that applied test-based instrument to adequately capture competence growth.

In the second study, I focused on *mathematics-specific* TPCK, proposing it to be knowledge necessary to provide high-quality instruction with technologies in mathematics. Using a self-developed and piloted instrument to assess mathematics-specific TPCK (consisting of text vignettes describing specific mathematical teaching problems), I empirically examined the relationship between TPCK, PCK and TK and investigated whether PCK is a sub-facet of TPCK or whether TPCK is a distinct knowledge component.

In study three, I developed a mathematics-specific intervention to investigate whether evidence-based short-term interventions could be successful in developing pre-service teachers' TPCK. Across these studies, I carefully considered contextual variables such as participants' motivational characteristics and demographics, too, in order to obtain an even more comprehensive picture on mathematics-specific knowledge regarding technology integration.

The collective findings from this dissertation indicate that TPCK has primarily been approached and viewed from a technology-cantered perspective, as opposed to a subject-specific perspective (study 1). Additionally, while mathematics-specific PCK and TPCK are statistically related, they seem to be distinct knowledge components, highlighting the necessity to specifically focus on mathematics-specific TPCK in pre-service teacher training (study 2). Lastly, it seems possible to foster pre-service teachers' mathematics-specific TPCK in an intervention, that adheres to principles from both general education research and mathematics education (study 3).

Together, the present dissertation provides a thorough investigation into how teachers' knowledge for teaching mathematics has been defined in the past, and how it could be assessed and fostered adequately in the future. Consequently, these findings offer practical guidance, emphasizing key aspects to be considered for designing test-based assessments and training programs, and thereby laying the groundwork for the advancement of technology-related research in mathematics education for the future.

Zusammenfassung

Die Mathematik spielt in unserer sich schnell verändernden Welt eine zentrale Rolle, da sie technischen Fortschritt vorantreibt, wissenschaftliche Durchbrüche ermöglicht und das kritische Denken fördert. Sie ist somit Voraussetzung für die Bewältigung komplexer globaler Herausforderungen. Die Förderung mathematischer Kenntnisse von Schüler*innen wird in der Bildungspolitik daher als zentral angesehen. In diesem Zusammenhang wird digitalen Medien das Potenzial zugeschrieben, Schüler*innen beim Erwerb mathematischer Kompetenzen zu unterstützen. Damit sich dieses Potential allerdings entfalten kann, müssen die Technologien von Lehrkräften sinnvoll in den Unterricht integriert werden. Das Professionswissen von Lehrkräften wird dabei als entscheidende Voraussetzung dafür angesehen, Technologien so einzusetzen, dass das konzeptionelle Verständnis der Schüler*innen für Mathematik gefördert wird. Dieses Professionswissen wird unter dem Begriff Technologisches-Pädagogisches-Inhaltswissen (TPCK, engl. für *technological pedagogical content knowledge*) zusammengefasst, eine Wissenskomponente, die über andere Wissenskomponenten wie fachdidaktisches und technologisches Wissen hinausgeht. Trotz der großen Relevanz für das Bildungswesen und auch darüber hinaus ist jedoch nur wenig über die genaue Struktur von TPCK bekannt, was vermutlich auf die überwiegende Verwendung von Selbsteinschätzungsbögen in entsprechenden Studien zurückzuführen ist, welche keine hohe Validität aufweisen. Weiterhin erschwert der Mangel an reliablen Testinstrumenten die Untersuchung der Beziehung zwischen TPCK und anderen Wissenskomponenten, und Erkenntnisse darüber, wie (angehende) Lehrkräfte effektiv auf den Unterricht mit Technologien im Mathematikunterricht vorbereitet werden können, können nur schwer abgeleitet werden, da Daten basierend auf selbsteingeschätztem Wissen nur einen ungefähren Anhaltspunkt für tatsächlichen Kompetenzzuwachs liefern können.

Vor diesem Hintergrund verfolgt die vorliegende Dissertation das Ziel, eine umfassende Untersuchung von mathematikspezifischen TPCK vorzunehmen, mit besonderem Augenmerk

darauf, wie dieses Wissen auf objektive Weise gemessen und wie es im Rahmen von mathematikspezifischen Kurzinterventionen gefördert werden könnte. Um diese Ziele zu erreichen, wurden insgesamt drei empirische Studien durchgeführt. In der ersten Studie wurden innerhalb eines systematischen Reviews 166 Interventionen in Primärstudien inhaltsanalytisch ausgewertet, um zu untersuchen, ob TPCK vorwiegend aus pädagogischer, technologischer oder fachspezifischer Perspektive verstandenen wurde. In einer anschließenden Meta-Analyse wurde die Effektivität der inkludierten Interventionen untersucht. Im Gegensatz zu früheren Meta-Analysen wurden hierbei nur Studien einbezogen, die leistungsbezogene Messinstrumente verwendeten, um Kompetenzzuwachs adäquat zu erfassen. In der zweiten Studie wurde der Fokus auf *mathematikspezifisches* TPCK gelegt, und es wurde untersucht, inwieweit dieses Wissen mit mathematikdidaktischem und technologischem Wissen zusammenhängt. Insbesondere lag der Fokus darauf zu untersuchen, ob sich TPCK und mathematikdidaktisches Wissen empirisch trennen lassen. Für die Durchführung der Studie wurde ein selbstentwickeltes und validiertes Instrument zur Messung von TPCK verwendet. Für die dritte Studie wurde eine mathematikspezifische Kurzintervention entwickelt, um zu untersuchen, ob evidenzbasierte Kurzzeitinterventionen zur Entwicklung von TPCK angehender Mathematiklehrkräfte beitragen können. Über alle drei Studien hinweg wurden verschiedene Kontextvariablen einbezogen, um ein umfassendes Bild von TPCK zu erhalten.

Insgesamt deuten die Ergebnisse daraufhin, dass TPCK in erster Linie aus einem technologiezentrierten und nicht aus einer fachspezifischen Perspektive betrachtet wurde (Studie 1). Außerdem scheinen mathematikdidaktisches und mathematikspezifisches TPCK zwar in Zusammenhang zu stehen, aber dennoch voneinander getrennte Wissensfacetten darzustellen, was die Notwendigkeit unterstreicht, sich in der Lehrkräfteausbildung auf mathematikspezifisches TPCK zu konzentrieren (Studie 3). Außerdem hat sich in Studie 3 gezeigt, dass forschungsbasierte Kurzinterventionen, die sich an etablierten Prinzipien der allgemeinen Bildungsforschung und der Mathematikdidaktik orientieren, das

Professionswissen angehender Mathematiklehrkräfte über die Integration von Technologien in den Mathematikunterricht (also mathematikspezifisches TPCK) wirksam verbessern können.

Insgesamt bietet die vorliegende Dissertation eine umfassende Untersuchung darüber, wie das Professionswissen von Lehrkräften für den Mathematikunterricht in der Vergangenheit konzeptualisiert wurde und wie es in Zukunft angemessen erfasst und gefördert werden könnte. Infolgedessen bieten diese Ergebnisse sowohl eine praktische Orientierungshilfe, indem sie Schlüsselaspekte hervorheben, die bei der Gestaltung testbasierter Aus- und Fortbildungen zu berücksichtigen sind, als auch wichtige theoretische Einsichten in die Struktur des Wissens zum Einsatz digitaler Technologien in den Mathematikunterricht. Die Dissertation liefert damit eine bedeutsame Grundlage für die Weiterentwicklung der mathematik- und technologiebezogenen Forschung für einen Mathematikunterricht der Zukunft.

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List of Abbreviations

AIC	Akaike information criterion
BIC	Bayesian information criterion
CFA	Confirmatory factor analysis
CFI	Comparative fit index
CK	Content Knowledge
COACTIV	Cognitive activation in the classroom: The Orchestration of learning opportunities for the enhancement of insightful learning in mathematics
EIS	Enactive iconic symbolic
ICC	Intraclass correlation coefficient
ICT	Information and communication technology
JOL	Judgment of learning
PCK	Pedagogical Content Knowledge
PISA	Program for international student assessment
PK	Pedagogical Knowledge
PRISMA	Preferred reporting items for systematic reviews and meta-analyses
RMSEA	Root mean square error of approximation
RQ	Research question
SEM	Structural equation model
SQD	Synthesis of qualitative evidence
SRMR	Standardized root mean squared residual
TCK	Technological Content Knowledge
TEDS-M	Teacher education and development study: Learning to teach mathematics
TEFL	Teaching English as a foreign language
TK	Technological Knowledge
TPCK	Technological Pedagogical Content Knowledge
TPK	Technological Pedagogical Knowledge
WLE	Weighted likelihood estimate

1 Introduction

1.1 Problem Statement

The recently published PISA results caused an uproar in education policy and beyond. One of the study's main findings yielded "an unprecedent performance drop" (OECD, 2023, p. 44) in the competences of 15-year-old students in the past decade. The decline of students in mathematics competencies is particularly concerning considering the central role of mathematics in general education (Winter, 1995) and, consequently for today's society (e.g., Kollosche et al., 2023). As the relationship between student performance and their teachers' competencies has been empirically warranted in the context of mathematics education (Blömeke et al., 2014; Hill et al., 2005; Kunter, Baumert et al., 2013), much research has been conducted to examine the professional knowledge of mathematics teachers as a sub-facet of teachers' competencies (Baumert & Kunter, 2013). Such research has resulted in rich insights into how professional knowledge for mathematics teaching could be conceptualized, assessed, and fostered. At the same time, research strands investigating and assessing professional knowledge for mathematics teachers have neglected a crucial element in its conceptualization and assessment which has become increasingly significant in education and likely contributed to the PISA results: knowledge of digital technologies. Despite empirical evidence that technologies hold the potential to support student's conceptual understanding of mathematics (Drijvers et al., 2016; Rolfes et al., 2022), there is a lack of research that examines the specific professional knowledge needed to teach mathematics with new technologies.

Drawing from generic education research, the *T*echnological *P*edagogical *a*nd *C*ontent *K*nowledge (i.e., TPACK; Mishra & Koehler, 2006) model seems a promising model in helping to examine technology-related professional knowledge of mathematics teachers. The TPACK-model extends Shulman's Pedagogical Content Knowledge (1986) comprising different knowledge components that interrelate and combine to give rise to Technological Pedagogical and Content Knowledge (TPCK) which is considered the essential pre-requisite for high-quality teaching and therefore received great attention from both researchers and practitioners (Hew et al., 2019). However, prior research on TPCK has identified several research desiderates that hinder the understanding and assessment of respective knowledge in the context of mathematics. First, TPCK seemed to have been conceptualized differently across disciplines (Angeli & Valanides, 2009; Schmid et al., 2020a). Second, to date, TPCK has mainly been assessed by means of self-report questionnaires (Koehler et al., 2012; Willermark, 2018), a method which has been critiqued for potential validity issues (Lachner et al., 2019; Scherer et al., 2017; von Kotzebue, 2022). Third, it remains an open question how to effectively design pre-service teacher training programs to improve mathematics-specific TPCK (Schubatzky et al., 2023; Voogt et al., 2013). Brantley-Dias and Ertmer (2013) summarized these desiderates within the research on TPCK succinctly as follows:

> Research is needed to clearly describe and delineate (a) what that knowledge looks like in the different disciplines, (b) how that knowledge can be measured within each domain, and (c) how that knowledge can be promoted and developed effectively within each domain. (p. 121)

1.2 Objectives and Structure of the Dissertation

Following Brantley-Dias and Ertmer's (2013) call, the overarching goal of the present dissertation was to provide a thorough examination of (pre-service) teachers' professional knowledge regarding technology integration in mathematics targeting the three desiderate outlined above. To do so, I conducted a total of three studies which aimed at investigating different aspects of TPCK related to its conceptualization, assessment, and development. In the first study, I synthesized and analysed prior conceptualizations in the TPACK-literature within a comprehensive systematic review. To identify researchers' underlying conceptualization, I investigated how the TPACK-model has been adapted for the design of interventions aimed at enhancing knowledge regarding technology integration. Focusing on interventions based on the model allowed me to investigate how the model was implemented in real-world settings. This way, I was able to scrutinize the TPACK-components deemed necessary by researchers for the development of TPCK. For this review, I expanded the focus beyond mathematics to explore how TPCK has been understood across subject domains. The aim was to identify whether TPCK has mainly been viewed from a pedagogical, technological, or subject-specific perspective.

For the second study, I conceptualized TPCK from a mathematics-specific perspective and examined the extent to which mathematics-specific TPCK is empirically related to mathematics-specific PCK and generic knowledge on technologies (i.e., TK). In contrast to the majority of prior research that applied self-reported questionnaires (Koehler et al., 2012; Willermark, 2018; results of study 1) which have been considered limited in assessing TPCK (see chapter 5), I developed, validated and implemented a test-based mathematics-specific TPCK instruments to assess TPCK objectively, accommodating the dominant call in the TPACK-literature for more performance-based measures (Agyei & Keengwe, 2014; Lachner et al., 2019; Schmid et al., 2020a; von Kotzebue, 2022).

In the third and last study included in this dissertation, I developed an evidence-based three-week intervention to investigate whether a short mathematics-specific intervention on technology integration is effective in fostering pre-service teachers' mathematics-specific TPCK. In contrast to the procedure of prior interventions aimed at fostering TPCK (see results of the systematic review, study 1), the effectiveness of the intervention was evaluated using test-based instruments applied within a robust quasi-experimental design.

Together, these studies focused on understanding the unique aspects of mathematics-specific TPCK, exploring methods to assess it, and identifying effective strategies for its development. Thus, this dissertation provides valuable insights for both mathematics pre-service teachers and educators, equipping them for a future enriched with technologies.

The remainder of this dissertation is organized as follows: The next chapter (i.e., chapter 2) begins with a broad overview of research on technology-enhanced mathematics teaching providing definitions central to this dissertation's topic. Subsequently, chapter 3 introduces the core focus of this dissertation, the TPACK-model, as a conceptualization of subject-specific knowledge for technology integration, tracing its origins from Shulman's (1986) Pedagogical Content Knowledge model to its adaptation and conceptualization in mathematics education. I will then review and critically discuss recent research on TPCK (i.e., the central knowledge component of the TPACK-model) focusing on its conceptualization (chapter 4), assessment (chapter 5), and development (chapter 6), while addressing critical issues not explicitly described within the included studies. In Chapter 7, I will formulate the overarching research goals for this dissertation and outline the structure of my studies addressing these goals. The three studies themselves are then included as three subsequent separate chapters (chapters 8, 9 and 10). Finally, in chapter 11, I will conclude with an overall discussion on the implications drawn from the findings of my studies.

2 Teaching Mathematics with Technologies

2.1 What are Technologies? A Working Definition

A broad distinction is often made between traditional technologies, like chalk and blackboards, and digital or new technologies, such as computer hardware and software, as exemplified in Thurm (e.g., Mishra & Koehler, 2006). Within the context of mathematics education, numerous taxonomies have been introduced to systemize the role of technologies for mathematics teaching and learning (see Clark-Wilson et al., 2020, for a detailed overview), with a specific emphasis on digital technologies. For example, Drijvers (2015) differentiated between the didactic role of technologies while *doing mathematics* on the one hand and while *learning mathematics* on the other. Whereas the role of technologies in doing mathematics "refers to outsourcing work that could also be done by hand" (Drijvers, 2015, p. 3), such as finding the roots of a quadratic function, their role for learning mathematics is specifically related to the context in which technologies are used to support students' development of mathematical knowledge. Relatedly, Barzel et al. (2009) and Thurm (2019) divided digital technologies into learning environment and tools. According to this differentiation, learning environments are educator-designed spaces that integrate content, communication methods, and instructional strategies, such as learning management systems. Tools, conversely, are flexible aids designed for a variety of problem-solving tasks. The most common tools are dynamic geometry software, spreadsheets, function plotters, and computer algebra systems (CAS) as detailed by Heintz et al. (2014). Some tools also combine features of several of these tools within one operating system offering great flexibility to switch between representations. Consequently, such tools have been coined multi-representational tools (Heintz et al., 2014; Thurm & Barzel, 2020).

Throughout this dissertation, the term *mathematics-specific technologies* refers to digital technologies used for learning mathematics, such as multi-representational tools or any of the digital tools most prominent in the context of technology-enhanced mathematics education (i.e., dynamic geometry software, spreadsheets, function plotters, computer algebra systems, and multiple representational tools). In contrast, the term *technologies* pertains to digital technologies in general.

2.2 Technology-Enhanced Teaching Quality

The term teaching quality comprises attributes of classroom teaching which are generally considered good or effective teaching reflected in "standards for teacher education and teaching" (Darling-Hammond, 2021, p. 296). Therefore, teaching quality is a central aspect to be considered when speaking of effective technology integration. The conceptualization of teaching quality varies across countries (Darling-Hammond, 2021). In Germany, teaching quality is prominently conceptualized along three dimensions: Cognitive activation, instructional support, and classroom management (Praetorius et al., 2018).

Cognitive activation involves task-specific teaching strategies designed to facilitate students' deep cognitive engagement (e.g., Backfisch, 2022). Such engagement might be fostered by activating students' prior knowledge and facilitating the exploration and explanation of relationships of mathematical objects (Klieme et al., 2006). Cognitive activation can be furthered differentiated in several subdimensions, which include the stimulation of higher cognitive processes through activating tasks, classroom discussions that aim at insisting on justifications, connecting prior knowledge and feedback and contingent support (Ufer et al., 2023). In this light, the teaching quality is considered specifically high, when the instruction "encourages students to discover and understand the meaning underlying procedures, to discuss the relationships between concepts, to compare different solution strategies, and to solve non-routine problems" (Lipowsky et al., 2009, p. 528). For a comprehensive discussion on the specific role of cognitive activation in mathematics education, see Leuders and Holzäpfel (2011).

The dimension *instructional support* – also known as supportive climate (Lipowsky et al., 2009) or simply student support (Praetorius et al., 2018) – represents teaching in which students are supported in reaching and remaining in deep learning-process (or higher-level thinking, see Lipowsky et al., 2009). Instructional support is commonly ensured by providing feedback and adaptive scaffolding that take the students' individual pre-requisites into account (Backfisch, 2022; Lipowsky et al., 2009).

Classroom management, on the other hand, refers to the extent to which the teacher is able to ensure that time in the classroom is spent on engaging students in cognitively challenging tasks (Lipowsky et al., 2009). Therefore, *good* classroom management requires the teacher to "maintain a smooth and calm learning environment without disruptions and interpersonal conflicts" (Backfisch, 2022, p. 26).

Empirical research has thoroughly examined the connection between high-quality teaching and student's learning outcomes (see Alp Christ et al., 2022, for an overview). These studies generally indicated a positive link, though the degree of connection varied (see also Lipowsky et al., 2009, for a detailed overview on empirical evidence).

Against this background, it is generally agreed on that the decision to include technologies in the classroom should be guided by contemplating their affordances for supporting teaching quality (see Backfisch, 2022, for a detailed definition of technology-enhanced teaching quality).

2.3 Potentials of Technologies to Enhance Students' Conceptual Understanding in Mathematics

A prominent indicator for teaching quality is students' learning outcomes[1]. In mathematics education, high-quality teaching is commonly associated with teaching that

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[1] Note here that an underlying assumption of the present dissertation is that learning outcomes are observable and quantifiable following the outcome-based education paradigm (Spady, 1994).

explicitly focuses on enhancing students' *conceptual knowledge* of mathematical concepts next to *procedural knowledge* (e.g., Crooks & Alibali, 2014). Whereas conceptual knowledge refers to an understanding of mathematical concepts, principles, and relationships (knowing the "why" behind mathematical facts), procedural knowledge involves the 'how-to'—the methods and algorithms used in solving mathematical problems (Hiebert & Lefevre, 1986; Rittle-Johnson & Alibali, 1999). Against this background, it is not surprising that empirical research findings suggested that conceptual knowledge is often taught within a principle-oriented explanation (cf. conceptual instruction, Lipowsky et al., 2009) over a procedure-oriented one (Perry, 1991; Weinhuber et al., 2019). Given the crucial role of conceptual knowledge in mathematics education (Crooks & Alibali, 2014; Hiebert & Lefevre, 1986), this dissertation specifically focuses on ways to integrate technologies in a principle-oriented way to foster students' conceptual understanding.

To date, several reviews investigated the potentials of technologies for students' learning relating them to critical aspects of mathematics education (Bray & Tangney, 2017; Cevikbas et al., 2023; Engelbrecht & Borba, 2023; Molina-Toro et al., 2019; Olive et al., 2009). Although mostly theoretically driven, these reviews' findings have also been backed up empirically by a growing body of meta-analyses in mathematics education literature (see Young, 2016, for a review of meta-analyses). These potentials were – for example – outlined and summarized by Clark-Wilson et al. (2020) and include the support of constructive approaches such as student-centred problem-based learning (Barzel & Möller, 2001; Thurm et al., 2023), the accessibility of abstract mathematical objects through visual representations (Drijvers et al., 2016; Rolfes et al., 2022), the reduction of unnecessary and distracting calculations in order to concentrate on conceptual aspects of the content (Bauer, 2015; Scaife & Rogers, 1996), and adaptive teaching (Corno, 2008; Prediger et al., 2022). To provide an example, technologies like dynamic geometric software offer the possibility to externalise representations of an abstract mathematical object, and dynamically link different representations (e.g., algebraic term and the graph of a function) to make their connection explicit (see Bauer, 2015, for an overview of multiple, dynamic representations in mathematics education). Such representations are key in mathematics as those “are the only way of gaining access” (Duval, 2000, p. 61; see also Salle et al., 2023, for an overview on the role of representations in mathematics education) to make mathematical objects accessible. It is not surprising, then, that there exist a growing body of empirical evidence that learning with multiple representation tools, such as GeoGebra, positively effects students’ conceptual understanding of functions (Rolfes et al., 2022).

3 Professional Knowledge of Teachers

In the previous chapter, I explained how technologies can be used to enhance teaching quality which in turn increases the likelihood to improve students' conceptual understanding of mathematics. However, these potentials do not unfold automatically. Instead, there is a consensus in research that teachers' professional knowledge plays a decisive role in unfolding technologies' potentials (Bray & Tangney, 2017; Drijvers et al., 2016; Drijvers et al., 2010; KMK, 2023; Petko, 2012; Thurm et al., 2023). The present chapter outlines recent research regarding the conceptualization of mathematics teachers' professional knowledge to teach with technologies. To begin with, I will situate professional knowledge as the crucial component within the broader construct of competency. Then, I will discuss Shulman's (1986) conceptualization of knowledge specific to the profession of teaching and how it has been adapted for mathematics-specific knowledge, before investigating how Mishra and Koehler (2006) extended Shulman's conceptualization to encompass knowledge of emerging technologies.

3.1 Professional Knowledge as a Crucial Sub-Facet of Competence

Professional knowledge is considered a key-requisite for teachers to exploit technologies' potential and to provide high quality teaching in mathematics (Clark-Wilson et al., 2020; Thurm et al., 2023). Baumert and Kunter (2013) identified knowledge as a sub-facet within the broader spectrum of teachers' competence. In their framework, teachers' competence is recognized as a multifaceted construct, encompassing not only professional knowledge but also aspects of motivational orientation, such as self-efficacy beliefs, and non-cognitive aspects such as self-regulatory skills and teaching enthusiasm (Baumert & Kunter, 2013). In the context of mathematics education, beliefs regarding technology integration have been considered and investigated extensively (Thurm, 2019; Thurm & Barzel, 2020). In contrast, professional knowledge regarding technology integration, has not yet been comprehensively investigated in the context of mathematics education to date.

3.2 Pedagogical Content Knowledge as Knowledge Specific to the Profession of Teachers: Revisiting Shulman

As outline above, professional knowledge is considered a key-requisite of teachers to provide high quality teaching (Shulman, 1986). Hence, one of the key endeavors in mathematics education has been to conceptualize and provide key characteristics of professional knowledge central to the profession of teachers. A prominent theoretical conceptualization of such knowledge was provided by Shulman (1986), who posited professional knowledge as an interplay of two basic knowledge components: (1) Content Knowledge (CK), that is deep knowledge about the content taught that goes beyond students' learning objectives, and (2) Pedagogical Knowledge (PK), which relates to generic knowledge about teaching and students' learning. According to this conceptualization, it is not enough to be an expert of the content taught (i.e., having high CK), nor to be a pedagogical expert (i.e., having high PK). Instead, teachers need to integrate and link both knowledge components – giving rise to Pedagogical Content Knowledge (PCK) – so that fruitful *subject-matter* teaching and learning can take place (Ball et al., 2008; Shulman, 1986). Although related, Shulman (1986) conceptualized PCK as theoretically distinct from both PK and CK. Shulman argued that PCK is knowledge specific to the profession of teaching. In this light, PCK encompasses knowledge of "ways of representing and formulating the subject that make it comprehensible to others" (Shulman, 1986, p. 9) as well as "an understanding of what makes the learning of specific topics easy or difficult" (p. 9). Here, Shulman also explicitly referred to possible misconceptions of students, thereby focusing on their perspective during learning. Hence, PCK includes the understanding of how to present and adapt the subject matter to make it accessible and understandable to students. Also, Shulman (1986) stressed that PCK is knowledge situated in the act of teaching claiming that not each representation can be learned through textbooks, but rather in "the wisdom of practice" (p. 9). Shulman's conceptualization of PCK has been widely acknowledged in educational research, while simultaneously being criticized for a number of reasons including a lack of theoretical grounding and empirical applicability (Depaepe et al., 2013).

To account for this criticism and to develop respective assessment instruments on firm grounds, researchers from the field of mathematics education adapted and differentiated PCK for mathematics which resulted in a rich repertoire of different conceptualizations of mathematics-specific PCK (Depaepe et al., 2013). For example, in the comparative Teacher Education and Development Study: Learning to Teach Mathematics (TEDS-M; Blömeke et al., 2014), PCK was conceptualized along two dimensions which roughly corresponded to viewing PCK from either a content-related or a pedagogical-related perspective on PCK (see Döhrmann et al., 2012, for a detailed conceptualization of PCK in TEDS-M). The items corresponding to the content-angle mainly included subject matter-oriented questions of teaching and learning mathematics, such as the subject-specific diagnosis of student solutions (Buchholtz et al., 2016). The items corresponding to the pedagogical angle, on the other hand, assessed knowledge about underlying principles of mathematical education including psychological-related approaches to identify students' misconceptions, various teaching and learning methodologies and classroom setups, as well as curricula and educational standards specific to mathematics teaching. However, this differentiation between the two dimensions was only considered in the development of the items, but not taken into account during the analyses (Buchholtz et al., 2016) which has been a subject to criticism (Kilian, 2018).

Next to the TEDS-M study which aimed at comparing teacher preparation programs across different countries and their effects on teachers' competencies, the COACTIV study (Professional Competence of Teachers, Cognitively Activation Instruction, and the Development of Student's Mathematical Literacy; Kunter, Baumert et al., 2013) also built upon

Shulman's PCK (1986) to conceptualize mathematics-specific PCK. The COACTIV study aimed at investigating the level of PCK of in-service teachers (as compared to the TEDS-M study whose sample was pre-service teachers). A primary goal of this study was to explore the relationship between teachers' level of competencies (including professional knowledge such as PCK) with their student achievement (Kunter, Klusmann., 2013). In COACTIV, mathematics specific PCK was conceptualized along three dimensions (Krauss et al., 2008). These dimensions included knowledge of mathematical tasks, knowledge of student misconceptions and difficulties, and knowledge of mathematics-specific instructional strategies (Krauss et al., 2008). In a related study project, a research group from the USA investigated PCK of primary mathematics teachers with a focus on specialized content knowledge needed for effective teaching (Ball et al., 2008; Hill et al., 2004). The construct, they called mathematical knowledge for teaching, encompassed both CK and PCK related aspects of Shulman's (1986) notion providing a clear conceptualization for PCK in the context of mathematics education (Ball et al., 2008).

In summary, Pedagogical Content Knowledge has been investigated and conceptualized intensively in the discipline of mathematics education (see Depaepe et al., 2013, for an extensive overview of mathematics-specific PCK conceptualizations). Although different to some extent, these conceptualizations share common key characteristics as outlined by Depaepe et al. (2013). Based on the findings of their review, researchers seemed to agree that CK is a pre-requisite of PCK, and that PCK is specialized knowledge for the profession of teachers in the sense that it is "necessary to achieve the aims of teaching" (Depaepe et al., 2013, p. 15). Moreover, mathematics-specific PCK encompasses understanding of specific ways to make mathematical concepts understandable for students. The authors also found that most conceptualizations viewed PCK as practical knowledge, i.e., knowledge "that teachers need for and apply in the act of teaching" (p. 15).

3.3 Adding Technological Knowledge to Shulman's PCK: The TPACK-Model

With the advent of new technologies, the profession of teaching has inherently become more complex (Margerum-Leys & Marx, 2002; Thurm et al., 2023). In this light, several conceptualizations emerged that attempted to account for this new complexity by extending Shulman's PCK framework. One of the earliest example was provided by Margerum-Leys and Marx (2002) who introduced the terminology "PCK of educational technology" (p. 446) in 2002. They regarded PCK of educational technology as "understandings for teaching with technology which arise from knowledge of technology as it is applied in classroom settings" (Margerum-Leys & Marx, 2002, p. 446). Their conceptualization highlighted the specificity of PCK in the context of using technology for teaching. Three years later, Angeli and Valanides (2005) introduced the term "ICT-related PCK" which they considered to be "the form of knowledge that makes a teacher competent to teach with ICT" (p. 294). Interestingly, the authors already coined the term "knowledge of technology" and argued that it was to become "another important category of the knowledge base of teaching" (Angeli & Valanides, 2005, p. 293) in the context of technology education. Contrary to the TPACK-model, which emerged a year later, the authors refrained from integrating this knowledge category as a novel basic component into Shulman's existing framework of PCK. Instead, the authors defined five loose principles they considered important for high quality technology integration. However, a detailed analysis of these principles reveals significant overlaps with what was to become the TPACK-model.

Finally, a year later, Mishra and Koehler (2006) introduced Technological Knowledge (TK) as a new basic knowledge component which they added as a third basic knowledge component to Shulman's PCK framework (besides PK and CK). According to Mishra and Koehler (2006), TK is "knowledge about standard technologies, such as books, chalk and blackboard, and more advanced technologies, such as the internet and digital video" (p. 1027). As discussed above (2.1), this dissertation specifically conceptualizes TK with a focus on knowledge about advanced, digital technologies acknowledging their widespread use in today's classrooms. Accordingly, TK as defined for the present dissertation includes "knowledge of operating systems and computer hardware, and the ability to use standard sets of software tools such as word processors, spreadsheets, browsers, and e-mail" (Mishra & Koehler, 2006, p. 1027).

The introduction of TK as a new central knowledge component gave rise to further technology-related knowledge components that emerge as a complex interplay of different knowledge components (i.e., Technological Pedagogical Knowledge, Technological Content Knowledge and TPCK) captured as intersections in the iconic Venn diagram (Figure 1). Together, the introduction of TK led to a total of seven interrelated knowledge components that are commonly subsumed under the Technological Pedagogical and Content Knowledge model (Mishra & Koehler, 2006). In particular, the centre of the Venn diagram accommodates Technological Pedagogical Content Knowledge (TPCK[2]), the knowledge considered crucial in order to provide high-quality teaching with technologies in a specific subject (Mishra & Koehler, 2006). The central role of TPCK when it comes to knowledge about technology integration in subject-matter teaching has been thoroughly discussed (Hew et al., 2019; Mishra & Koehler, 2006; Voogt et al., 2013).

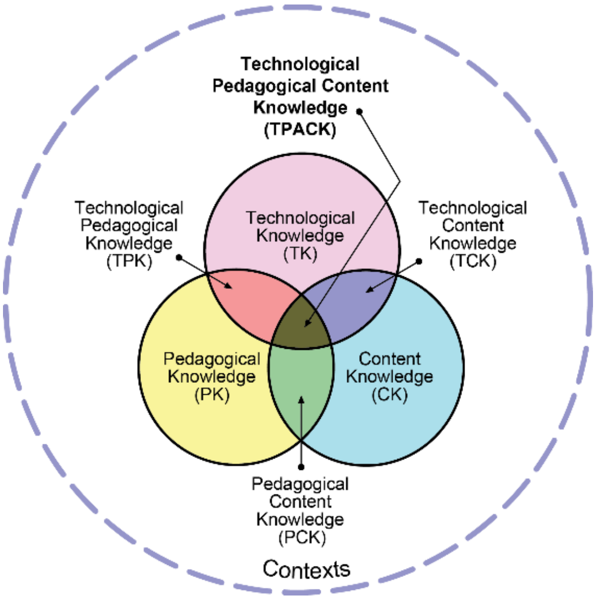
To illustrate the shift from PCK to TPCK in the context of mathematics education, imagine a mathematics teacher whose students learn the Pythagorean Theorem. These days – with technologies being widely available –, the teacher does not only need to anticipate possible misconceptions the students hold about the Theorem (e.g., not recognizing the geometrical nature of the theorem), know how to counter them and how to make sure that the students are

[2] Note that in this dissertation (except for study 3, chapter 10), I use the term TPCK when addressing the specific central component of the TPACK-model. In contrast, I use the term TPACK when addressing the whole model as a framework including each of its knowledge components (i.e., TK, PK, CK, TPK, TCK, PCK, TPCK).

cognitively activated throughout the lesson by purposeful orchestration (i.e., teacher has high level of PCK); Instead, the teacher further needs to recognize the technological affordances certain tools have (e.g., illustrating the necessary and sufficient condition of a 90° angle with the help of animations), and to know how to use them (i.e., TK) to support and deepen students' learning. Similar then to how PCK emerges from the interplay of PK and CK (Shulman, 1986), the teacher needs to integrate PCK with TK in order to reach TPCK.

Figure 1

The TPACK-Model



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Despite its relevance for teaching with technologies, research on TPCK as the central TPACK-component has identified several desiderate which relate to how TPCK is conceptualized, how it is measured, and how it is fostered. To address these issues of TPCK in the context of mathematics was the main goal of the present dissertation which is why the following chapters discusses TPCK in light of these desiderate summarizing prior research findings.

4 Conceptualization of Technological Pedagogical Content Knowledge

The first overarching goal was to investigate conceptualizations of TPCK prevalent in the literature. This chapter therefore presents three different perspectives to systematically conceptualize TPCK, i.e., the central knowledge component of TPACK required for effective technology integration into subject-matter teaching. First, I will discuss the different perspective on TPCK as either *knowledge* or *skill*. Second, I will discuss TPCK in light of the ongoing debate regarding its theoretical underpinnings as either *transformative* or *integrative* in nature. Lastly, I will introduce another way to examine TPCK which relates to the idea of viewing TPCK from either a pedagogical, subject-specific or technocentric perspective.

To lay common ground for the three included studies, the chapter ends with a description of how I conceptualized mathematics-specific TPCK for this dissertation. This conceptualization will be used for the subsequent development of my TPCK assessment instrument (chapter 5) and the design of the mathematics-specific intervention to foster TPCK (chapter 6).

4.1 TPCK: Knowledge or Skill?

When Mishra and Koehler (2006) introduced the TPACK-model, they did not clearly distinguish between knowledge and skill (Brantley-Dias & Ertmer, 2013). Although frequently used interchangeably, teachers' knowledge and skill represent distinct concepts which are often defined as subcomponents of competence (Baumert & Kunter, 2013; Weinert, 2001). In this context, knowledge is seen as theoretical and encompasses a teacher's comprehension of a particular subject area, as well as an understanding of what constitutes effective teaching (e.g., Fenstermacher, 1994).

Skill, on the other hand, is the ability to perform actions or tasks in practice (e.g., Baumert & Kunter, 2013). In other word, skill refers to the practical application of theoretical knowledge, allowing individuals to perform tasks or actions proficiently. As such, they can be observed and measured in action. In this light, the notion of skill closely resembles what Orlikowski (2002) called *knowing in practice* or others *practical knowledge* (e.g., Depaepe et al., 2013).

In the context of TPACK, there has been a vivid debate on whether TPCK is knowledge or skill (Brantley-Dias & Ertmer, 2013). This distinction is in particularly critical as it effects the way TPCK is assessed (Willermark, 2018). For example, TPCK as skill is commonly assessed through observing (pre-service) teachers in the act of teaching, whereas TPCK as knowledge is often assessed through questionnaires detached from the act of teaching (Brantley-Dias & Ertmer, 2013). Relatedly, Willermark (2018) proposed a systematization in which TPCK is positioned along a spectrum. On this spectrum, one end represents TPCK as knowledge, while the opposite end represents TPCK as competence referring to knowledge as applied in authentic contexts.

4.2 TPCK: A Unique Knowledge Component or the Sum of Its Sub-Components?

Another debate circling around TPCK manifests itself in how TPCK is related to the other TPACK-components (i.e., TK, PK, CK, PCK, TPK, TCK), and how it is developed. Prominently, the debate of TPCK of being either *integrative* or *transformative* in nature has helped in framing this debate and is pivotal in understanding its role in education (Angeli & Valanides, 2009). According to the integrative view, TPCK is not a distinct or unique body of knowledge; instead, TPCK is directly related to the other TPACK-components. In particular, growth in first- (i.e., TK, PK, CK) and second-order knowledge components (i.e., TPK, PCK, TCK) directly translates to growth in TPCK. Put differently, TPCK is regarded as a combination or accumulation of the different basic TPACK-components which can be integrated on the spot during the act of teaching (Angeli et al., 2016; Angeli & Valanides, 2009).

In contrast, the transformative view posits TPCK to be a distinct and unique knowledge component that goes “beyond simple integration, or accumulation, of the constituent knowledge bases" (Angeli et al., 2016, p.21). In this view, growth in any of the other TPACK-components would not automatically translate to growth in TPCK. Rather, teachers would need to receive explicit support to be able to integrate different knowledge components to reach TPCK.

The distinction between these two perspectives – integrative and transformative – is not just theoretical but has important practical implications, too (Aldemir Engin et al., 2022; Angeli et al., 2016). If TPCK is viewed as integrative, the focus of teacher education and professional development might be on targeting Technology-, Pedagogy-, and Content knowledge separately. However, if TPCK is viewed as transformative, the emphasis might shift to fostering innovative thinking and encouraging educators to explore new possibilities transcending the intersections of TPACK-components.

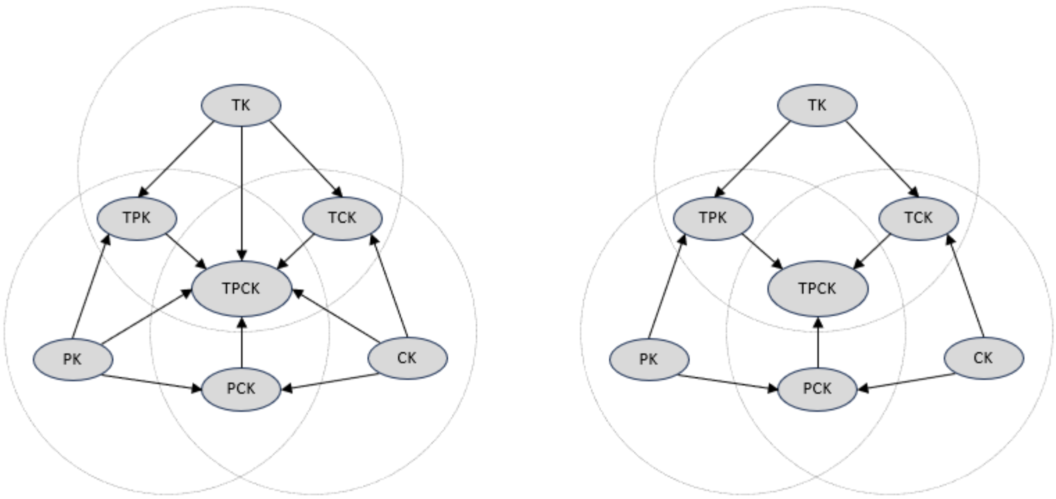
How has TPCK been understood regarding its theoretical underpinnings of TPCK as either integrative or transformative? Early researchers who adopted the PCK model to include knowledge about new technologies (see. 3.3) differed in this regard. For example, whereas Margerum-Leys and Marx (2002) introduced PCK of educational technology as knowledge that is "unique to the use of educational technology" (p. 446) which does not "derive from, nor does it necessarily apply to, teaching without educational technology" (p. 446) (i.e., following the transformative view), other researchers seemed to adhere to the integrative view (Angeli & Valanides, 2009; Angeli et al., 2016) focusing on TPACK-components different to TPCK believing that "growth in any related constructs (i.e., content, technology, pedagogy) automatically contributes to growth in TPCK" (Angeli & Valanides, 2009, p. 158).

Given the significance of the nature of TPCK for the design of assessments (see chapter 5) and effective development programs (see chapter 6), empirical investigations addressing this debate are surprisingly scarce and have mainly been based on qualitative studies (Angeli et al., 2016). The findings of these studies, conducted in the early years after TPACK's introduction, suggested that TPCK was transformative as "growth in the related constructs of TPCK without particular instruction, revealed that growth in the related constructs of TPCK without particular instruction, targeting exclusively the development of TPCK, did not automatically result in TPCK growth" (Angeli et al., 2016, p. 21).

Only recently, however, first quantitative studies were conducted to replicate these qualitative findings (Schmid et al., 2020a; von Kotzebue, 2022). The findings of these studies also suggested that TPCK is transformative in nature (Schmid et al., 2020a; von Kotzebue, 2022). However, it is questionable whether the empirical operationalization of the integrative vs transformative distinction in these studies have adequately represented the underlying theoretical views. To elaborate, Schmid et al. (2020a) conducted a cross-sectional survey-study with *N* = 117 pre-service who answered several items that assessed each TPACK-component individually. Based on this sample, the authors empirically operationalized the distinction between transformative and integrative by contrasting two different structural equation models (SEM) reflecting either of these views (see also von Kotzebue, 2022). In both models, TPACK-components and their relationships with each other were specified. As indicated in Figure 2, these models only differed with regard to the way that these relationships were represented. In the model corresponding to the integrative view, *each* TPACK-subcomponent (i.e., TK, PK, CK, PCK, TPK, TCK) was modelled to have a direct effect on TPCK. In contrast, in the model representing the transformative view, the basic TPACK-components (i.e., TK, PK, CK) were not modelled to have a direct effect on TPCK, but instead only an indirect effect on TPCK via the second order TPACK-components (i.e., PCK, TCK, TPK). Although valuable in enlightening the debate around TPCK's theoretical nature, this operationalization does not seem to correspond fully with the theoretical distinction drawn by other researchers, as those researchers did not explicitly distinguish between direct and indirect influences of basic TPACK-components (i.e., TK, PK and CK) and second-order TPACK-components (i.e., TPK, TCK, PCK) (e.g., Angeli & Valanides, 2009). Instead, they based this distinction on whether TPCK is distinct from *each* of the other TPACK-component (Angeli et al., 2016; Angeli & Valanides, 2009). Therefore, I argue, that results based on the empirical operationalization proposed by Schmid et al. (2020a) must be taken with caution. In this light, I suggest addressing this ambiguity in two steps acknowledging both the theoretical conceptualization of TPCK (e.g., Angeli & Valanides, 2009) and its empirical operationalization (Schmid et al., 2020a; von Kotzebue, 2022). Following Schmid et al.'s (2020a) empirical operationalization of TPCK's nature, I propose to *compare* the influences of basic knowledge components and second-order knowledge components on TPCK in a two-step process. First, I suggest comparing effects on TPCK within one model directly (instead of two separate models). This allows a clearer distinction between the influence of basic TPACK-component (such as TK) on TPCK and hybrid TPACK-component (such as PCK). In a second step, I propose to examine how much variance in TPCK can be explained by including TPACK-components of both basic (e.g., TK) and hybrid TPACK-components (e.g., PCK). If a large amount of unexplained variance remains, one could conclude that TPCK is uniquely distinct from these TPACK-components, and instead is affected by knowledge components that go beyond the subcomponents of TPACK (Angeli et al., 2016). Therefore, this procedure was applied in study 2.

Figure 2

Operationalization of the Integrative and Transformative View of TPCK



Note. The figure is an adapted version of the figures found in Schmid et al. (2020a) and von

Kotzebue (2022). The left figure represents the integrative view; the right figure represents the transformative view.

4.3 TPCK: Subject-Specific, Technocentric or Pedagogical?

To date, several conceptualizations of TPCK exist that put much emphasis on some knowledge components while seemingly putting less emphasis on others. For example, a variety of conceptualizations exist that seemed to have highlighted the role of knowledge regarding specific technologies when it comes to successful technology integration (Brantley-Dias & Ertmer, 2013). These technologies included interactive whiteboards (Jang & Tsai, 2012), the Web (Lee & Tsai, 2010), digital games (Hsu et al., 2015), geographic information systems (GIS; Hong & Stonier, 2015) or artificial intelligence (Celik, 2023). According to these conceptualizations, TPCK is highly dependent on knowledge about the use of *specific* technologies in pedagogical contexts. Therefore, these conceptualizations may be thought of as viewing TPCK from a technological perspective. Drawing upon the TPACK Venn diagram, this conceptualization can be thought of approaching TPCK by T(C)K

In contrast, conceptualizations in different subject domains such as geography (G-TPACK; Doering et al., 2009), biology (von Kotzebue, 2022), science (TPASK; Jimoyiannis, 2010) or mathematics (Guerrero, 2010) highlighted the subject-specific nature of TPCK (Brantley-Dias & Ertmer, 2013; Voogt et al., 2013) suggesting that TPCK is approached from a subject-specific angle (i.e., CK or PCK).

Again other conceptualizations seemed to have focused on a pedagogical angle of the TACK-model by highlighting different aspects relevant for teaching with technologies across subjects such as student-focused instruction (Saengbanchong et al., 2014) or inquiry-based learning (Maeng et al., 2013). According to these conceptualizations, TPCK does not seem to depend on knowledge of technologies for specific subjects. Hence, this conceptualization can be thought of as approaching TPCK from a generic pedagogical angle (i.e., PK or TPK).

In sum, different conceptualizations of TPCK may have placed different emphases on some TPACK-components while possibly placing less emphasis on other components. Against this background, I argue that these different strands of conceptualizations can be systemized by highlighting the specific knowledge angle from which TPCK is being viewed, further helping to clarify different conceptualizations prevalent in the TPACK literature. This idea of conceptualizing TPCK, however, is not completely new. In 2009, Cox and Graham already concluded that it is crucial for the design of interventions to know by which "path" (p. 69) educators believe that teachers arrive at TPCK, summarizing this situation as follows:

> Some seem to believe that teachers should first acquire TCK and then TPACK will come as they enact their knowledge in a pedagogical context. Others feel that it is first necessary to have a knowledge of the general uses of technology in the classroom (TPK) before one can fully utilize subject-specific methods. (p. 69)

To date, no systematic approach has investigated TPCK with regard to which knowledge view on TPCK has been prominent in the TPACK literature. A related approach, however, was provided by Dewi et al. (2021) who found in a systematic review based on the publication outlet of 184 primary studies that most of them were published in technology-based and education-oriented journals. This might hint towards a predominant technological or pedagogical view of TPCK. However, the outlet of a publication only provides a distal proxy for the angle from which TPCK was conceptualized. Therefore, in my review (i.e., study 1), I focused on more direct forms to investigate the angle view of TPCK by examining TPCK-interventions with respect to which TPACK-components (i.e., TK, PK, CK, TPK, TCK, PCK, or TPCK) have been explicitly targeted in the course of these interventions. This way, I could deduce which TPACK-components have been considered most important in the development of TPCK by the researchers, and hence deduce information regarding the conceptualizations of TPCK in the TPACK-ecosystem (see study 1, for more details).

4.4 Mathematics-Specific Professional Knowledge to Integrate Technology into Teaching: Towards a Comprehensive Conceptualization

In this dissertation, I have conceptualized TPCK from a mathematics-specific perspective Building on Mishra and Koehler's (2006) original framework and informed by the aforementioned discussions, I propose the following definition of mathematics-specific TPCK: Mathematics-specific TPCK is the specialized knowledge base of teachers needed to provide high quality teaching with technologies which may manifest itself in observable teaching skills. It encompasses profound understanding of school-related mathematical content and the optimal methods for teaching it using technologies, taking into account students' existing preconceptions and understanding of their learning processes (cf. mathematics-specific PCK, Depaepe et al., 2013). As such, mathematics-specific TPCK extends beyond mathematics-specific PCK by adding a distinct element of knowledge that specifically addresses the complexities introduced by new technologies. Following the conceptualization of the COACTIV model (Baumert & Kunter, 2013), a key premise of the mathematics-specific TPCK as defined here is that it is teach- and learnable in the context of pre-service teacher training and professional development courses.

I want to explicitly note that I deviated from prior conceptualizations of mathematics-specific TPCK that mainly formulated key characteristics of this knowledge component without clarifying its connection to different TPACK-components (Guerrero, 2010). Instead, my conceptualization of mathematics-specific TPCK builds upon previously sound conceptualizations of mathematics-specific PCK (see 3.2) adapting them by adding an extra knowledge component (TK) which specifically addresses new technologies. In this light, mathematics-specific TPCK as conceptualized in this dissertation can be thought of the knowledge component that emerges when integrating mathematics-specific PCK with TK acknowledging knowledge about the affordances of technologies for high quality instruction in mathematics.

5 Assessment of Technological Pedagogical and Content Knowledge

The second overarching goal of the present dissertation was to develop and validate a test-based instrument that assesses mathematics-specific TPCK so that it can be used to investigate the inherent structure of mathematics-specific TPCK (study 2) and to evaluate the effectiveness of a short intervention implemented for pre-service mathematics teachers (study 3). In this light, this chapter presents prior findings on TPCK assessments and a short overview of the mathematics-specific TPCK instrument I developed and validated.

5.1 Overview of Existing Instruments to Assess TPCK

Since the introduction of the TPACK-framework in 2006 (Mishra & Koehler, 2006), numerous researchers have endeavoured to develop reliable and valid instruments to measure TPCK. However, seven years after the introduction of the TPACK-model, Brantley-Dias and Ertmer (2013) were prompted to state that “If TPACK is to become a useful construct for researchers and teacher educators, we must be able to measure it” (p 108). This statement illustrated two things: First, it underlined the significance for reliable and valid measurements of TPCK to push the field forward. Second, it showed that even seven years after its introduction, there was still a long way to go to assess TPCK reliably and validly.

To systemize existing TPCK assessments, Abbitt (2011) brought forward a broad classification to distinguish between self-report assessments and performance-based assessments (see also Willermark, 2018). Performance-based assessments refer to strategies that include assessing TPCK in the context of teaching-authentic scenarios and include the analysis of artefacts produced by (pre-service) teachers such as lesson plans (Backfisch et al., 2020, 2024; Schmid et al., 2020b) and the evaluation of actual teaching performance within micro teachings (Aldemir Engin et al., 2022; Aydogan-Yenmez & Gökçe, 2017) or authentic class room scenarios (Bustamante, 2019; Njiku, 2023). Even though these approaches allow for a comprehensive and detailed analysis of (pre-service) teachers' TPCK, they are limited in their application as they require extensive set ups and coding time. As a result, they are difficult to implement in large-scale studies. Additionally, performance-based assessments often lack explicit validation criteria, hence studies based on these assessments are limited in their transferability (Voogt et al., 2013).

In contrast, self-report measures provide a cost-efficient and easily implemented strategy. Self-report measures refer to assessment strategies in which participants are asked to rate the degree of agreement with a given statement on a Likert scale. For example, one of the most adopted and used TPACK measurement instruments based on self-assessments stems from Schmidt et al. (2009). In their survey, they included items tapping on each of the seven TPACK-components (i.e., TK, PK, CK, TPK, TCK, PCK, TPCK) to assess the level of pre-service teachers. Although cost-efficient and easily evaluated, self-report measures have been discussed a sub-optimal strategy to assess TPCK (Brantley-Dias & Ertmer, 2013; Lachner et al., 2019; Scherer et al., 2017; Schmid et al., 2020b; Voogt et al., 2013; see also study 2 for a comprehensive overview of problems associated with self-report measures). In particular, it has been noted that their reliability may depend on peoples' ability to assess one's own knowledge accurately (Abbitt, 2011; Brantley-Dias & Ertmer, 2013). Though plausible, it remains empirically unclear whether this assumption holds. To test for the relationship between the accuracy of self-reported TPCK and performance level, one needs to assess TPCK by both approaches and include measures of accuracy. This is what I did in study 2.

5.2 Which Assessment Strategy has been most Prominent in TPACK Research?

In the last decade, several comprehensive reviews have been conducted to investigate which assessment strategy had been most prominent in TPACK research (Abbitt, 2011; Koehler et al., 2012; Mouza, 2016; Tseng et al., 2020; Voogt et al., 2013; Willermark, 2018). Across all reviews, the results indicated that self-report measures were the most prominent way (pre-service) teachers' TPCK had been assessed. However, these reviews were based on a comparatively old sample of studies (Abbitt, 2011; Koehler et al., 2012; Voogt et al., 2013; Willermark, 2018), or restricted to domain-specific publications (Tseng et al., 2020). Therefore, an updated, comprehensive review based on studies across all contexts taking into account published papers from 2006 onwards (when TPACK was introduced) is needed to investigate whether the predominance of self-reports still pervade to this day (which was one of the research questions addressed in study 2).

The findings of the existent reviews further suggested that test-based instruments had been neglected (e.g., Willermark, 2018). Test-based instruments commonly refer to strategies that evaluate participants' knowledge through standardized tests, and thereby differ from performance-based instruments that rely on assessing TPCK in mostly authentic settings[3] (Willermark, 2018). Test-based instruments are a common method to assess knowledge in large scale studies such as PISA or COACTIV, and have been prominently applied to assess mathematics-specific PCK in the past (Buchholtz et al., 2016; Hill et al., 2004; Krauss et al., 2008). In this light, it is surprising that respective test-based TPCK instruments are still lacking in mathematics education (see study 2 for a comprehensive overview of scarce examples assessing TPCK by test-based instruments in different subject) as indicated by the large amount of recently published papers still relying on performance-based instruments and/or self-reports (Aldemir Engin et al., 2022; Bueno & Niess, 2023; Morales-López et al., 2021; Njiku, 2023; Rakes et al., 2022).

[3] Sometimes, researchers classified test-based instruments as a sub-category of performance-based instruments (e.g., von Kotzebue, 2022). In the TPACK-literature, both terms are often seemingly used interchangeably. In this dissertation, I explicitly distinguish between performance-based and test-based instruments at this point. For the review study (i.e., study 1), however, I also considered test-based instruments to be contained within performance-based ones.

The lack of test-based instruments is a research gap that needs to be addressed urgently as such instruments would be suitable to diminish the limitations of both self-report and performance-based measures prevailing in the TPACK-literature. For example, test-based instruments, unlike self-report measures, urge participants to *apply* their knowledge and therefore do not suffer from possible bias induced by low metacognitive competences (see study 2 for a detailed description). Also, test-based instruments can be designed in a way that explicitly requires respondents to draw on *subject-specific* knowledge; a capability that has been identified as a limitation in self-report measures (Voogt et al., 2013). Moreover, due to their lower cost and ease of use with larger samples, test-based instruments are more feasible for studying TPCK' structure or evaluating the effectiveness of courses aimed at enhancing TPCK compared to performance-based measures.

5.3 Developing a Mathematics-Specific Test-Based Instrument to Measure TPCK

Against this background, I developed a *test-based* instrument to assess *mathematics-specific* TPCK. To do so, I adopted a cognitive perspective (i.e., TPCK as knowledge, see 4.3) on TPCK suggesting that TPCK could be assessed detached from the context of real classroom situations (Baier & Kunter, 2020). Following Krauss et al. (2008), the mathematics-specific TPCK instrument contained eight open-ended questions that were based on text-vignettes which depicted prototypical mathematic-specific teaching problems. I specifically chose to use open-ended items (instead of multiple-choice items) as it allowed me to analyse authentic solutions for the contextualized teaching problems that are relevant for mathematics teachers. In the words of Döhrmann et al. (2012), open items allow "more insight into the professional knowledge of future teachers" (p. 338). In formulating the teaching problems for each item, I aligned with insights from mathematics education research, particularly those related to students' misconceptions. For example, it is well documented that many learners face challenges in mastering the conceptual understanding of fractions (see Reinhold et al., 2020, for an overview on conceptual understanding of fractions). One item was therefore based on this well-known issue by formulating a teaching scenario in which pre-service teachers were asked to describe how to integrate technologies addressing students' misconceptions regarding the multiplication of two fractions ("Correctly multiplying two fractions, $\frac{a}{b} \cdot \frac{c}{d} = \frac{ac}{bd}$, seems to be an easy task for your students. However, at the same time, they find it difficult to reason that the product of two fractions may be smaller than each of the corresponding factors as they believe that multiplying two numbers always results in larger numbers"). Similarly, research demonstrated that learners have difficulties in applying the Pythagorean Theorem correctly in different contexts (e.g., Hutapea et al., 2015), a finding which served as the basis for another teaching problem formulated one of the items (see Table 1).

For each of the eight items included in the self-developed TPCK-instrument, respondents were asked to *describe* and *justify* the possible use of technologies to overcome them mathematics-specific classroom problems (e.g., identifying and addressing misconceptions of students, see Table 1 for an overview of an item's structure). Thus, following my conceptualizing of mathematics-specific TPCK (see 4.4), students had to integrate their pedagogical content knowledge (PCK) in contexts related to digitalization and link it with their technological knowledge (TK). The justification, the participants provided in each item, further acknowledged the necessity of teachers to "adequately reason about the use of technologies" (Lachner et al., 2024, p. 7) when integrating technologies into the classroom.

The development and validation of the test instrument is detailed in study 2 (see 9.3.2.1) and 3 (see 10.2.3.2)[4], as well as in Richter (2021). Moreover, a complete overview of the items,

[4] Note that the chronological sequence in which the studies were conducted does not match their order of appearance in this dissertation. Specifically, the original TPCK instrument was first employed in the third study (see 10.2.3.2), while the adapted version was used in the second study (se 9.3.2.1). For a full explanation of the development process of the TPCK instrument, refer to Richter (2021).

together with the coding manual, which was primarily developed by Lunowa (2023), can be found online (https://osf.io/ag6fz/?view_only=89fb16cd42834f79b1c0b82ed52ac3e3) as supplementary material.

Table 1

General Structure of the Mathematics-Specific TPCK Items Together with an Exemplary Item

General structure of an item	Example item
Formulation of a typical mathematics-specific teaching problem in class	The Pythagorean Theorem is often used incorrectly by students in exercises, which is due to possible misconceptions of the theorem. For example, the theorem is often applied to triangles without right angles, or the formula $a^2 + b^2 = c^2$ is memorized without understanding its geometric relationship.
Asking for the use of technologies to overcome the problem	As a teacher, how could you use educational technologies as a teacher to help students develop a better understanding of the Pythagorean Theorem so that your students apply it correctly in exercises in the future?
Asking for a justification	Please justify your answer

6 Development of Technological Pedagogical Content Knowledge of Pre-Service Teachers

The third overarching goal of the dissertation was to develop an evidence-based three-week intervention to foster pre-service mathematics teachers' TPCK. Given that the intervention was evaluated in the context of a larger project comprising several subjects, the intervention's general procedure followed design principles from generic educational research, such as the SQD-model (Synthesize Qualitative Data, Tondeur et al., 2012, see study 3). The specific content taught within these three weeks, however, differed across subjects in accordance with the conceptualization of TPCK as knowledge to teach with technologies for a *specific subject* matter. Against this background, the following chapter will focus exclusively on the unique aspects of the intervention pertinent to mathematics. To start, I will delve into mathematics-specific literature which identified design principles deemed effective for the development of pre-service teachers' mathematics-specific TPCK.

6.1 Fostering Mathematics-Specific TPCK: What do we Know from Research?

Prior research on the development of mathematics-specific TPCK has a rich history and resulted in different design principles considered effective in interventions (Aldemir Engin et al., 2022; Barzel & Selter, 2015; Niess, 2005; Rakes et al., 2022). In pre-service teacher education, these principles emphasized the importance of fostering *positive attitudes* towards technology integration, offering good-practice examples as *models*, encouraging *peer collaboration*, and promoting *reflective thinking* (Stapf and Martin, 2019; see also Barzel & Selter, 2015, for related design principles in the context of teachers' professional development). Another design principle of effective interventions evident from prior research on mathematics-related TPCK interventions is the importance of having pre-service teachers engage in *authentic design tasks*. These tasks commonly include activities like lesson planning (Agyei & Keengwe, 2014; Benning, 2021; Bonafini & Lee, 2021; Morales-López et al., 2021; Njiku et al., 2021), and conducting micro teachings (Açıkgül & Aslaner, 2020; Kartal & Çınar, 2022; Liang & Luo, 2015), enabling pre-service teachers to genuinely experience what it is like to integrate technologies into teaching.

Against this background, I carefully considered each of these design principles in developing a three-week intervention aimed at fostering pre-service teachers' mathematics-specific TPCK as detailed below.

6.2 The Design of the Mathematics-Specific TPCK Intervention

Given my conceptualization of TPCK as a unique knowledge component that requires specific training, I designed the mathematics-specific intervention with a particular focus on fostering TPCK rather than addressing other TPACK-components (such as TK) separately.

In line with the concept of "approximations of practice" (Grossman et al., 2009), the structure of the mathematics-specific intervention was divided into four parts which offered gradually more authentic teaching experiences for the pre-service teachers in the course of the intervention. Figure 3 gives an overview of the different phases of the intervention.

Figure 3

The Design of the Mathematics-Specific TPCK Intervention

In the first phase, knowledge on the use of technologies in mathematics was conveyed through an online learning module, following the Flipped Classroom approach (Lo et al., 2017). Alongside general aspects of teaching quality (Kunter & Trautwein, 2013), the module demonstrated how technologies could be integrated into mathematics instruction to enhance students' conceptual mathematical knowledge. These examples were provided via texts, via examples within digital tools (e.g., GeoGebra Worksheet) or via an instructional video. Throughout the module, which was implemented in a learning management software, the students answered short questions or provided short summaries of specific paragraphs to stay focused and cognitively activated. Such activities are also commonly known as *retrieval practice*; an umbrella term for learning activities focusing on recalling information from memory. A rich body of empirical research in education research demonstrated the superiority of retrieval practice activities for students' learning over study methods like rereading (Agarwal et al., 2021; Moreira et al., 2019). Content wise, the mathematics-specific examples included in the learning module mostly circled around the question of how multi representational tools (such as GeoGebra) can be used to highlight the relationship between different representations of a mathematical object (such as the term and the graph of a real function). Relatedly, another example included in this phase was the introduction of the Enactive-Iconic-Symbolic (i.e., EIS) theory in the context of digital technology. Originally formulated by Bruner (1974) as a generic learning theory, the EIS theory was intensively adapted by mathematics educators (Salle et al., 2023; Zech, 2002) acknowledging its importance for understanding mathematical concepts, the theory proposes three modes of representation, each considered essential for grasping a thorough understanding of a mathematical object: the *enactive* mode involves learning through action; the *iconic* mode involves learning through images and diagrams; and the *symbolic* mode involves learning through abstract symbols like algebraic terms (see Salle et al., 2023, for an overview on the role of the EIS theory in mathematics education). To adopt the theory for technology-enhanced teaching, I followed Ladel's (2009) adaptation of the EIS theory. By doing so, I showcased how teaching principles deemed important for mathematics education could be adapted to account for teaching with technologies. Again, this example highlighted the subject-specificity of TPCK by extending PCK to knowledge specific for teaching in a digital setting. Further examples demonstrated how technologies could be used for adaptive teaching (Corno, 2008; Tetzlaff et al., 2021), once more focusing on specific examples from mathematics education (Prediger et al., 2022; Reinhold et al., 2020). In sum, the first phase mostly centered on the design principle of presenting exemplary models of effective technology integration into mathematics, serving as references for pre-service teachers. The learning module was published as an Open Educational Resource (https://lms-public.uni-tuebingen.de/ilias3/goto.php?target=crs_6666).

After consolidating what the students learned from the module, the students were asked to create lesson plans in the second phase as a further approximation towards practice. While they were free to choose the learning objectives of the lesson, they were required to incorporate phases supported by technologies in their design. In this phase, the students worked in teams to support collaborative learning. They received constant feedback on their lesson plans from the instructor and revised their plans accordingly. The second phase of the intervention thus focused on the design principles of involving participants in real-world design tasks and fostering collaboration.

In the third phase, the pre-service teachers were asked to thoroughly prepare short teaching sequences from the lesson plans and carry them out in video-recorded micro teachings (Aldemir Engin et al., 2022). During the micro teachings, some pre-service teachers slipped in the role of students, whereas others concentrated on providing feedback on a sheet for the subsequent discission of the micro teachings. In this phase, students had the opportunity to adopt the role of a teacher, designing lessons to gain authentic experiences relevant to their future careers, as well as assuming the role of students, thereby gaining a multifaceted perspective.

In the last and final phase of the intervention, the students were asked to peer-feedback the other pre-service teachers' recorded micro teachings to initiate reflection, another key design principle for mathematics-specific TPCK acquisition. As they offered feedback, the pre-service teachers were also given a sheet with prompts designed to guide them in providing detailed feedback, specifically focusing on how technologies were employed to improve the quality of teaching (Franke et al., 2024).

In sum, in designing the three-week intervention, I carefully followed recommendations from generic educational research (Grossman et al., 2009; Tondeur et al., 2012) and further integrated several design principles from mathematics-specific research that have been discussed as being effective for developing pre-service teachers' TPCK (Stapf & Martin, 2019).

7 Overarching Research Questions and Structure of the Dissertation

As outlined above, research on mathematics-specific knowledge of how to integrate technologies effectively in the classroom has not been investigated comprehensively to date. This is surprising given the rich history of research on mathematics-specific PCK which lacked to explicitly take into account knowledge of technologies (Döhrmann et al., 2012). Drawing upon Mishra and Koehler's (2006) TPACK-model, the overarching goal of the present dissertation was to examine such knowledge regarding its conceptualization, assessment, and development. To approach this goal, I started by taking a broad perspective, that is, I investigated how TPCK has been conceptualized and assessed so far in the literature. To do so, I conducted a systematic review to answer the first main research question (RQ) of the present dissertation:

RQ 1) How has Technological Pedagogical Content Knowledge (TPCK) been conceptualized and assessed across subjects to date?

Another aim of this review study was to synthesize prior evidence regarding the effectiveness of interventions aimed at fostering TPCK. Therefore, I conducted a meta-analysis. In contrast to prior meta-analyses (Wilson et al., 2020) that relied on self-reports, my meta-analysis sample comprised only studies based on performance-based measures to adequately capture knowledge growth.

Following study 1, I conceptualized mathematics-specific TPCK (see 4.4) and developed as well as validated a test-based TPCK instrument (see 5.3). By employing this instrument together with test-based instruments that directly tapped mathematics-specific PCK and TK, I was able to investigate TPCK and its relationship to PCK and TK in study 2 shedding further light into the inherent structure of mathematics-specific TPCK. The overarching research question tackled by study 2 was as follows:

RQ 2) What is the empirical relationship between mathematics-specific TPCK, mathematics-specific PCK and TK. Do these relationships suggest a transformative or integrative view of mathematics-specific TPCK?

Finally, following my conceptualization of mathematics-specific TPCK as a unique knowledge component that needs deliberate practice, the last study of the dissertation shed light into the possibility of fostering pre-service teachers' mathematics-specific TPCK within an evidence-based three-week intervention. The overarching research question of the third study was as follows:

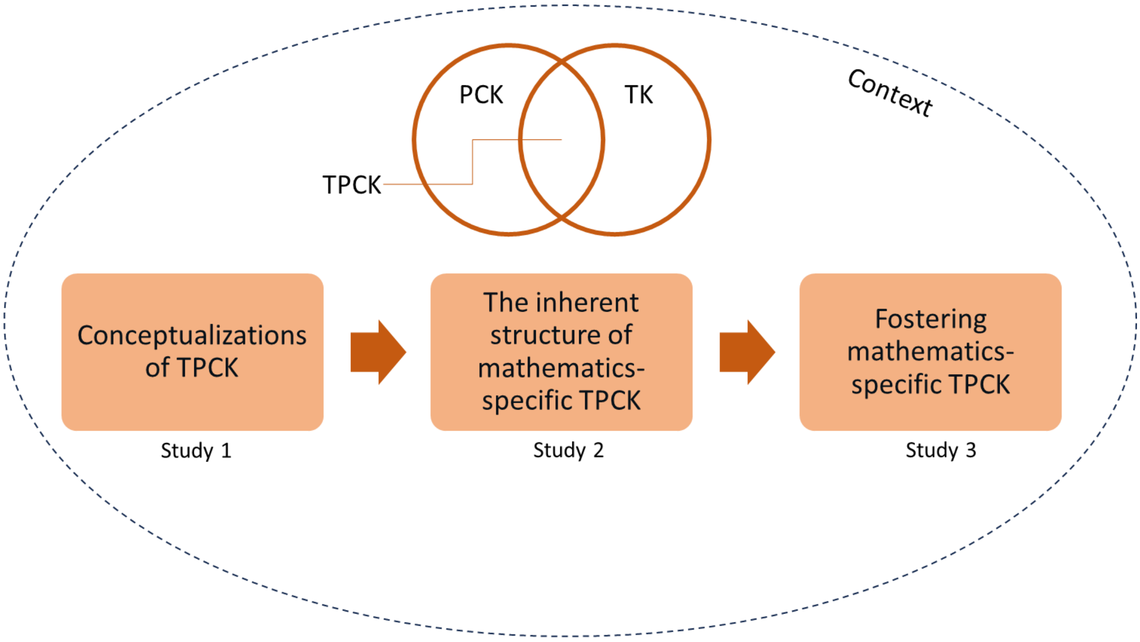
RQ 3) Is an evidence-based, mathematics-specific training module effective in fostering pre-service teachers' mathematics-specific TPCK?

The effectiveness of the intervention was evaluated as part of a larger study which comprised several interventions across various subjects (i.e., German, English, Philosophy, and Biology). Unlike most previous research on TPACK-based interventions, this study assessed participants' TPCK through test-based measures within a rigorous quasi-experimental research design, thereby providing robust evidence for the effectiveness of the interventions.

Figure 4 provides an overview of the three studies and their arrangement highlighting the key aspects related to each of the three research questions. Note that the central chart in Figure 4 is surrounded by dotted lines labeled "context". This underlines the crucial need to consider context in the TPACK-landscape (Brianza et al., 2022; Mishra, 2019). In accordance with that, each of the three studies took into account various contextual variables to offer a comprehensive picture on (mathematics-specific) TPCK. For example, in the review (i.e., the first study), contextual variables included macrolevel variables (Brianza et al., 2022) such as the region or the time the interventions took place, possibly effecting targeted knowledge components. In the second study, on the other hand, contextual variables under consideration included participants' demographics such as gender or age. Moreover, I considered prior experience of teaching in school as well as participants' ability to accurately self-assess their TPCK; contextual variables that may contribute to the weak link between self-reported and test-based instrument reported in the past (Abbitt, 2011). Finally, the intervention study (i.e., the third study) considered context on a micro-level by carefully considering plausible influencing factors contributing to the effectiveness of the interventions. These factors included pre-service teachers' prior knowledge before the intervention, motivational variables or the subjective support received by the instructors during the intervention (see study 3 for details).

Figure 4

Overview of the Dissertation



8 *Study 1*: A Systematic Review and Meta-Analysis on TPACK-based Interventions from the Perspective of Knowledge Integration

The content of this chapter has been accepted for publication as part of an article in a special issue of Computers & Education Open. Minor differences may still exist between this chapter and the final published version.

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Abstract

Designing effective interventions that foster (pre-service) teachers' knowledge to teach with technologies is paramount in education research. Researchers have prominently relied on the TPACK-model as theoretical foundation to design such interventions. However, a myriad of distinct TPACK-based interventions emerged, which likely targeted the different knowledge components of TPACK to varying extents. Given this diversity and the lack of performance-based measures to estimate competence growth, little is known about the effectiveness of respective interventions. In the present synthesis study, we therefore sought to systemize TPACK-based interventions regarding targeted knowledge domains across various contexts. Accordingly, we scrutinized which of the TPACK-components were explicitly targeted in TPACK-based interventions within the framework of a systematic review. Further, we conducted a subsequent meta-analysis based on studies applying performance-based measures to investigate whether the targeted knowledge domains affected the effectiveness of interventions. Based on a set of N = 163 primary intervention studies and one theoretical contribution, our analyses suggest that Technological Knowledge was the most prominent targeted TPACK-component. Interestingly, in more than 20% of the interventions, Technological Pedagogical Content Knowledge (i.e., TPCK) was absent although TPCK is considered crucial for successful technology integration. Results further revealed that researchers do not seem to have adapted the design of interventions on instructional contexts (such as the expertise level of the target audience). The results of the subsequent meta-analysis (N = 8) further provided no clear evidence that targeted TPACK-components affected the effectiveness of interventions.

Keywords: Technological Pedagogical Content Knowledge, TPACK-based interventions, Teacher professional development, Systematic review, Meta-analysis

8.1 Introduction

Professional knowledge is considered an essential prerequisite to teach with technologies in a meaningful way. Previous research, however, has demonstrated that teachers often face difficulties to successfully teach with technology (Backfisch, Lachner et al., 2021; Fraillon et al., 2019). Therefore, developing effective interventions[5] for (pre-service) teachers that aim at fostering professional knowledge for teaching with technology is paramount in education research (Lachner et al., 2021; Røkenes & Krumsvik, 2014; Tondeur et al., 2012; Yurtseven Avci et al., 2020). To design effective interventions, researchers have predominantly relied on the Technological Pedagogical and Content Knowledge model (TPACK; Mishra & Koehler, 2006) as a theoretical foundation; a model which posits the integration of different knowledge components (i.e., pedagogical-, content- and technology-related knowledge) as a crucial prerequisite for teaching with technology.

In the last two decades, a myriad of interventions has been developed which targeted the single knowledge components and the interchapters of TPACK (i.e., TK, PK, CK, TCK, TPK, PCK, TPCK) to varying extents (see De Rossi & Trevisan, 2018; Huang et al., 2022; Wang et al., 2018). These different realizations across TPACK-based interventions may have resulted in flaws regarding their comparability. Put differently, the extensive research conducted on TPACK-based interventions may have given rise to jangle-fallacies (Kelley, 1927; Marsh et al., 2019), meaning that various researchers possibly referred to the same construct (i.e., TPACK), when – at the same time – interpreting and implementing it differently in their interventions. To this end, this situation makes it difficult for practitioners as well as researchers to build their

[5] Note that for the purpose of the present study, we use the term interventions for any kind of strategies or programs described in studies that aim at fostering participants' professional knowledge regarding technology integration. For example, our use of the term comprises stand-alone teacher education courses, professional development courses for in-service teachers or (short-term) interventions in the word's traditional meaning (Hattie et al., 1996).

new interventions upon firm ground, and to judge the overall-effectiveness of previous TPACK-based interventions.

In this light, the present study seeks to (1) synthesize previous TPACK-based interventions regarding targeted knowledge domains, and (2) investigate whether the heterogeneity in their effectiveness may be explained by the diverse knowledge domains targeted in interventions. Accordingly, our procedure was two-fold. First, within the framework of a systematic review, we used a rich data set of n = 164 studies including TPACK-based interventions and investigated which TPACK-components were targeted by means of qualitative content analysis. Given that TPACK is highly context sensitive (Rosenberg & Koehler, 2015), we further explored in the review whether the targeted TPACK-components in interventions were dependent on contextual factors such as participant group composition (i.e., level of experience or subject domains of participants) or cultural setting of the intervention. Second, we evaluated the general effectiveness of these interventions and investigated whether and to what extent the targeted knowledge domains affected their effectiveness by means of a meta-analysis. Combining both approaches (i.e., systematic review and meta-analysis) helps to qualitatively and quantitatively portray the current TPACK-landscape in depth and guide future researchers in designing effective interventions fostering knowledge of teaching with technology (see Sims et al., 2021, for related approaches in the field of teacher professional development).

8.2 Theoretical Background

8.2.1 Professional Knowledge for Technology Integration: The TPACK-Model

One of the most prominent frameworks of professional knowledge for teaching with technology is the **T**echnological **P**edagogical **a**nd **C**ontent **K**nowledge (i.e., TPACK) model by Mishra and Koehler (2006). The TPACK-model extends Shulman's (1986) conceptualization of Pedagogical Content Knowledge (PCK) as the integration of Pedagogical Knowledge (PK) and Content Knowledge (CK) via a third component, namely Technological Knowledge (TK). Thus, the TPACK-model consists of seven knowledge components, which are regarded to be essential for teaching with technology (see Figure 5): Technological Knowledge (TK), Pedagogical Knowledge (PK) and Content Knowledge (CK), referred to as first-order TPACK-components, and more integrated forms of knowledge components, namely Technological Pedagogical Knowledge (TPK), Technological Content Knowledge (TCK), and Pedagogical Content Knowledge (PCK), so-called second-order components. Finally, these first- and second-order components merge to form Technological Pedagogical Content Knowledge (TPCK[6]), the core of the TPACK-model and the main target knowledge domain that TPACK-based interventions aim at in order to foster teaching with technology.

It is important to note that TPACK is situated knowledge and thereby contextually sensitive (Brianza et al., 2022; Mishra & Koehler, 2006; see also Berliner, 2001, for a general discussion on the situated nature of teacher knowledge). Accordingly, integrating technologies in subject-matter teaching does not happen in isolation. Instead, it has been recognized that teachers act within a complex setting that is influenced by contextual variables, such as students' characteristics or schools' cultural setting (see Brianza et al., 2022, and Rosenberg & Koehler, 2005, for comprehensive reviews on the role of context in TPACK research). Prominently, the influence of context on TPACK is highlighted in the Venn diagram (Figure 1) with the dotted circle surrounding the seven TPACK-components. In this light, it is reasonable to assume that researchers also adapted TPACK-based interventions to the different contexts in which they were implemented, leading to variations in the designs.

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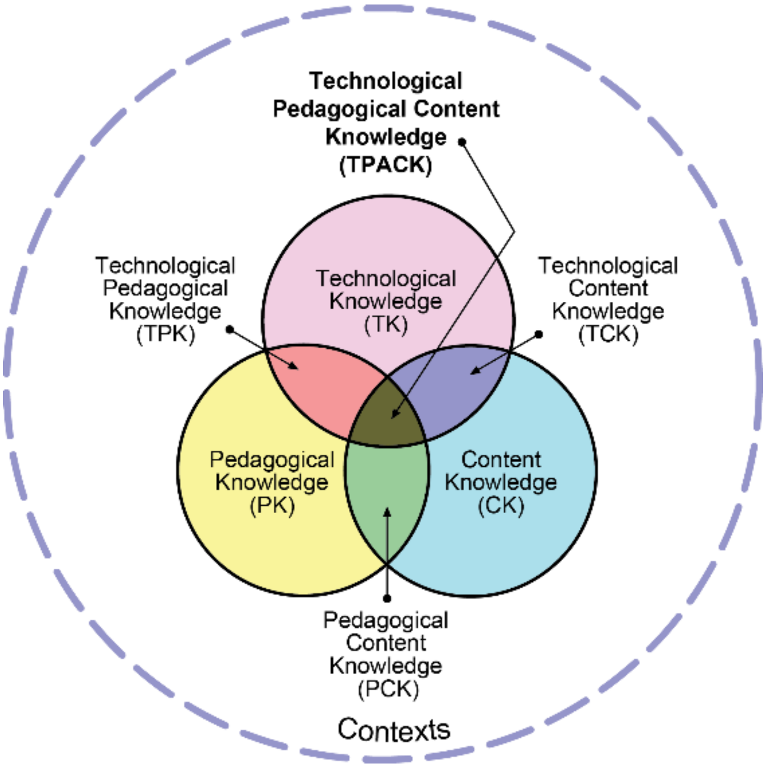
[6] In this study, we use TPCK to explicitly refer to the knowledge component of technological pedagogical content knowledge. In contrast, we use TPACK as a term instead to refer to the TPACK-model as a whole. This distinction for readability has been used before already (Schmid et al., 2020a; Schubatzky, 2023).

Figure 5

The TPACK Venn Diagram



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8.2.2 TPACK as a Theoretical Foundation to Design Interventions

Considering the prominence of the TPACK-model (Hew et al., 2019), as well as the involvement of subject-specific and generic disciplines in studying and adapting TPACK (Willermark, 2018), it appears plausible that researchers have developed a myriad of distinct TPACK-based interventions that potentially targeted different TPACK-components. Indeed, previous studies suggest that researchers approached knowledge for teaching with technologies from different TPACK-angles when designing interventions. For instance, in some TPACK-based interventions the central knowledge component TPCK was highlighted. An empirical example can be found in the study by Lachner et al. (2021). The authors designed a three-week TPACK-based module that aimed at enhancing subject-specific knowledge about technology integration of pre-service teachers. The training, which was implemented in regular subject-matter pedagogy courses, highlighted the importance of TPCK as the central knowledge component of the TPACK-model by explicitly showcasing the "distinct potential of the portrayed technologies from the perspectives of subject-matter pedagogies" (Lachner et al., 2021, p. 7). In this spirit, the participants were directly introduced to "subject-specific principles of technology integration" (p. 7) suggesting that the researchers targeted subject-specific PCK and TPCK explicitly, instead of merely focusing on knowledge of how to operate technologies (i.e., TK). Similarly, Max et al. (2022) approached TPCK by having pre-service teachers engaged in "media-based subject projects embedded in elective or mandatory seminars in the natural sciences" (p. 1162). They, too, started off the intervention by "using examples of integrating technology into subject lessons" (Max et al., 2022, p. 1163), hence focusing on TPCK. The authors also explicitly fostered PCK by discussing "criteria for good science teaching" (Max et al., 2022, p. 1163) excluding any technology-related aspects during this phase of training. Interestingly, in contrast to Lachner et al.'s study, they also targeted more generic knowledge components, such as TPK, as they discussed subject unspecific theories regarding technology integration (e.g., the cognitive theory of multimedia learning; Mayer, 2014).

Alternatively, researchers designed TPACK-based interventions that approached teaching with technology by targeting technology-related knowledge (i.e., TK and TCK) and placing less emphasis on providing training opportunities that directly targeted TPCK. For example, Mouza and Karchmer-Klein (2013) investigated how an undergraduate teacher education course could support pre-service teachers to learn how to teach with technology. In their course, the authors did not explicitly target TPCK by any of the courses' activities. Instead, their emphasis appeared to be on the operational aspects of (subject-specific) technologies (i.e., TK and TCK), leaving it to the participants to determine how to effectively implement these technologies in a pedagogically meaningful manner. Similarly, Peng (2020) evaluated the impact of the *Technology Teaching Assistantship (TTA) Program* on teacher educators' TPCK. In the program, teacher educators were trained to coach pre-service teachers in facilitating technology integration. Instead of highlighting the subject-specific nature of technology integration (i.e., TPCK), the participants were primarily exposed to generic principles of technology integration (e.g., the Substitution Augmentation Modification Redefinition Model; Puentedura, 2006), which suggests a focus on TPK. Additionally, they were provided with opportunities to train operational skills with specific devices such as the iPad, which suggest a focus on TK. Note, however, that in contrast to the aforementioned studies, the target audience were teacher educators who can be considered pedagogic experts in the field. Given their level of experience, it may be reasonable to suggest, that interventions aiming at enhancing TPCK of teacher educators may primarily target broader generic technology-related knowledge. However, the extent to which such pattern persists across the TPACK-landscape remains an open question due to the lack of comprehensive synthesis studies that are based on primary studies across varying contexts. Similarly, it remains unclear how other contextual factors, including participants' subject domains or the region in which the intervention was integrated, may have influenced the TPACK-components that were explicitly targeted in the course of interventions.

8.2.3 Jangle Fallacies of the TPACK-Model in Designing Interventions

The previous empirical examples suggest a plethora of different approaches to foster TPCK: Whereas some interventions fostering TPCK seem to have emphasized basic TPACK-components (i.e., TK, PK or CK) or second-order components (i.e., PCK, TPK, TCK), others seem to have targeted TPCK explicitly, suggesting that TPCK could theoretically be fostered by providing trainings on some TPACK-components, while ignoring others. The differences of targeted TPACK-domains between interventions may have emerged due to the unclear theoretical underpinnings of TPACK which mainly concerns the question of how TPCK is related to the other TPACK-components, and how it is developed. In particular, two opposing views have crystallized around these questions: The *integrative* view and the *transformative* view (Angeli & Valanides, 2009). Whereas the transformative view suggests that TPCK is a separate and distinctive knowledge component, which is developed over time via deliberate practice from other teacher knowledge structures, the integrative view suggests that TPCK is not a distinct knowledge structure. Instead, TPCK may be constructed on the fly by integrating separable knowledge components during teaching with technology. In this view, growth in any of the other TPACK-components would automatically translate to growth in TPCK. Accordingly, TPACK-based interventions could be effective in fostering TPCK when they "merely" target basic knowledge components (i.e., TK, PK, CK) or second-order components (i.e., TPK, TCK, PCK).

In this light, we argue that the immense research conducted on TPACK-based interventions may have given rise to jangle-fallacies, a term prominently used in the context of construct validity (e.g., Marsh et al., 2019), referring to the phenomenon of dissimilar constructs called the same. Adapting the notion of jangle-fallacies to the context of TPACK-based interventions, we can attest that researchers may have used the term TPACK to provide a theoretical framework for their interventions. However, the authors' specific interpretation and implementation of the TPACK-model may have varied largely across interventions, likely reflected in the nuanced differences regarding targeted TPACK-components. To this end, this situation makes it difficult to compare and build upon previous findings. Moreover, given the broad use of TPACK in research on interventions, we further need to understand possible relationships between targeted knowledge components and the contexts of the interventions' implementation, such as the target audience of the TPACK-based intervention (pre-service, in-service teachers, teacher educators; subject domain backgrounds), the subject-specificity of implementation, trends over time or the region in which the intervention was conducted.

To resolve the issue of possible jangle-fallacies and detect patterns across various contexts, synthesis studies investigating a broad range of interventions regarding their targeted TPACK-components are needed. In this light, surprisingly few reviews exist that have considered synthesizing TPACK-based interventions regarding targeted knowledge domains. For example, Huang et al. (2022) examined differences of targeted TPACK-components of professional development programs for in-service science teachers via a systematic review. The authors found that in less than 50% of the included studies, more than one TPACK-component was addressed. PK and PCK were the most frequently addressed TPACK-components, whereas TCK and TPACK were fostered to a less pronounced extent. However, the authors' emphasis was solely based on STEM interventions, making it difficult to transfer these findings to other subjects. Moreover, the authors based their review only on interventions with in-service teachers. Therefore, it is an open question to which extent these results translate to other target audiences with different levels of expertise, such as pre-service teachers or teacher educators.

Relatedly, there are only few meta-analyses that aim to aggregate findings regarding the effectiveness of TPACK-interventions (Schmid et al., 2024). However, previous meta-analyses synthesized empirical evidence which was primarily based on the analysis of self-reports. For instance, Young et al. (2013), investigated effects of TPACK-based interventions on participants' self-reported knowledge, based on eight studies. The authors obtained a significant effect of the TPACK-based interventions on self-reported TCK (d = 0.70), followed by a moderate effect size (d = 0.44) on self-reported TPCK (see also Wilson et al., 2020, for more recent findings). Although these findings may provide important evidence regarding participants' increases of perceived competence, the use of self-reports may not allow to infer potential implications regarding the actual acquisition of knowledge and skills to teach with technologies (see Lachner et al., 2021, for a critical discussion on self-reports). Therefore, meta-analyses that estimate the effectiveness of interventions based on studies applying performance-based measures are needed.

8.2.4 The Present Synthesis Study

Based on the previous evidence and potential desiderates, the main aim of the current synthesis study was to portray the current landscape of TPACK-based interventions and test for potential jangle-fallacies in the TPACK-ecosystem, as well as to investigate the effectiveness of TPACK-based interventions. Following a knowledge integration approach, we conducted a systematic literature search, and investigated which TPACK-components and combinations thereof were primarily targeted in previous TPACK-based interventions and whether these occurrences of targeted TPACK-components depended on contextual variables (e.g., targeted audience, trends over time or regional patterns). To scrutinize which TPACK-components were mainly targeted in interventions, we followed a finely grained content analysis approach instead of relying on distal proxies such as the implementation context of the interventions. Finally, we estimated the general effectiveness of previous TPACK-based interventions via a meta-analysis, and explored whether differences in the effectiveness of the interventions regarding technology integration could be explained by the different knowledge components addressed. These analyses should help disentangle possible jangle-fallacies, and researchers and practitioners alike gain a deeper understanding of previous knowledge constituents in TPACK-based interventions, and guide future iterations of TPACK-based interventions. Particularly, we investigated the following research questions:

RQ 1: Which TPACK-components have been targeted in previous TPACK-based interventions?

RQ 2: Do contextual variables affect the frequency of targeted TPACK-components?

RQ 3: Which combinations of TPACK-components have been frequently targeted together?

RQ 4: How effective were previous TPACK-based interventions regarding technology integration, and can the potential variability in the effectiveness be explained by differences in the targeted TPACK-components?

8.3 Method

To select relevant records that include TPACK-based interventions, we followed the multi-step process proposed by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework (Moher et al., 2016, Page et al., 2021). Upon identification of the final review sample, we applied qualitative content analysis (Mayring, 2015) to each study to scrutinize which TPACK-components were explicitly targeted in the interventions. Using this aggregated data, we then applied correlative analyses to explore possible similarities and differences across interventions (RQ 1—3). Lastly, we identified those studies from the review sample that applied performance-based measures as potential proxy for (pre-service) teachers‘ growth in competences for teaching with technology and conducted a meta-analysis to test their effectiveness (RQ 4). The respective steps are detailed in the following.

8.3.1 Literature Search

To obtain a comprehensive picture on TPACK-based interventions, we used five of the most prominent databases to identify relevant literature (Web of Science, PsycINFO, EriC, ScienceDirect, Google Scholar (first 100 results)), and applied the following broad search term:

‘(TPACK OR TPCK OR “technological pedagogical content knowledge” OR “technological-pedagogical-content-knowledge” OR “technological pedagogical and content knowledge”) AND teach’.*

In each database, we specified the language to be English and the time span to range from 2005 to 2022[7]to capture interventions implemented after Mishra’s and Koehler’s article that introduced the TPACK-model in 2006. To ensure the quality of included studies, we restricted

[7] Note that we used the year of the official publication within a journal’s volume, and not – for example – the date of the first ever available online publication.

our sample on journal articles. We first collected the records on the 30th of December, 2020, and updated our sample with a subsequent search on the 12th of January 2023. We accessed the databases via the network of the *blinded* University.

8.3.2 Identifying Relevant Literature

8.3.2.1 Identifying the Sample for the Review

The search within the five databases yielded a total of 3,595 records. These records were imported to the management system Rayyan (Ouzzani et al., 2016) where duplicates (*n* = 893) were removed automatically. In Rayyan, two independent raters screened each of the titles, abstracts, and key words. Based on pre-defined inclusion criteria (see below), the raters decided whether to include the record or not. The inclusion criteria were pre-registered (*blinded* link) using the R-template PreregRS (Schneider et al., 2022). According to these criteria, records were kept for subsequent data extraction if each of the following characteristics applied: The records…

- included TPACK or adaptions in the title, abstract or key words,
- reported interventions that aimed at fostering professional knowledge for teaching with technology that were grounded in the TPACK framework.
- were of either theoretical or empirical nature and contained rich descriptions of the interventions' design.

After rating the abstracts based on the first two criteria, there were few discrepancies between the two raters (in *n* = 66 of the records which roughly equaled 2.5%). In these cases, the respective full texts were screened together, and consensus was reached by discussion.

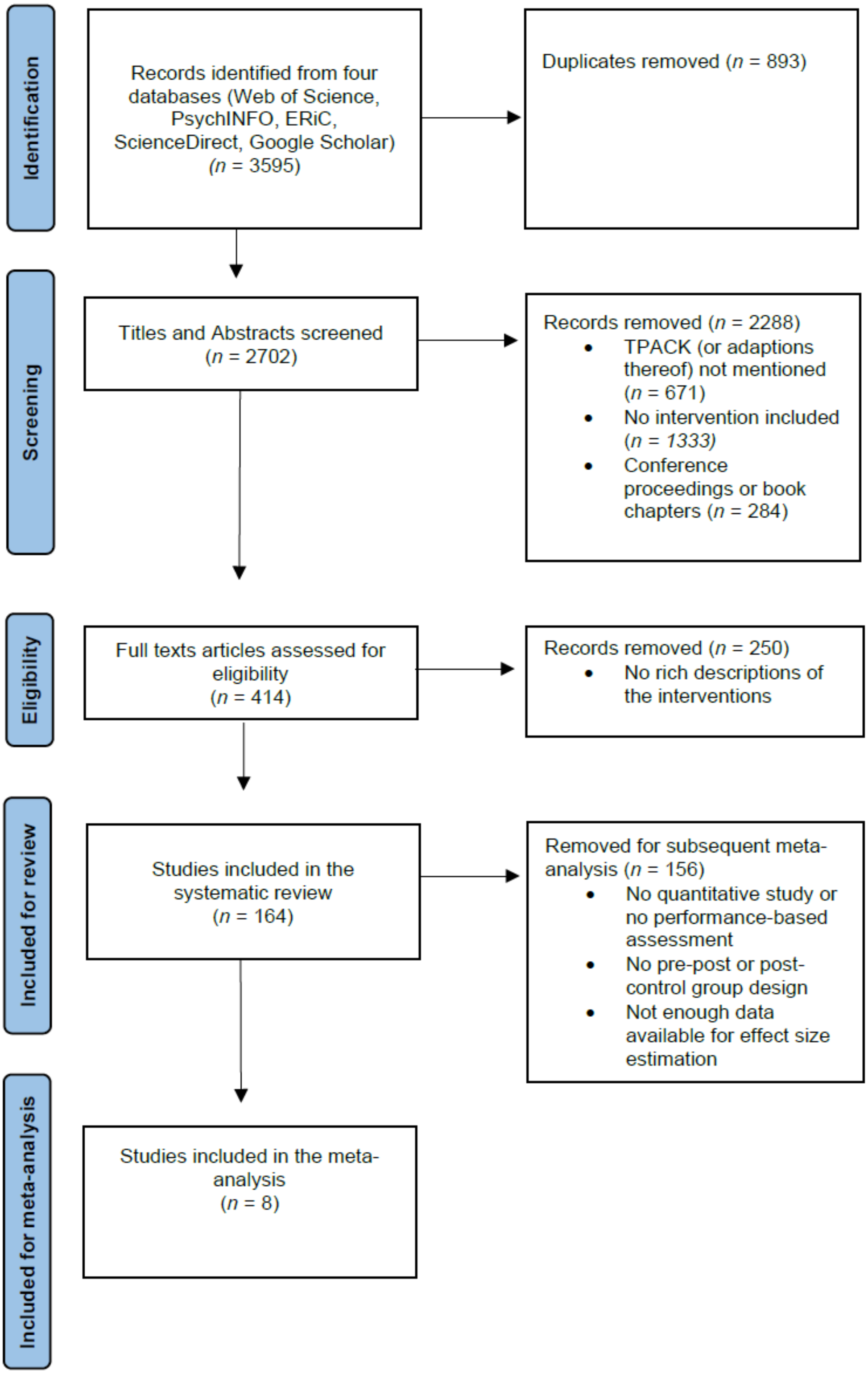
In a next step, *n* = 2702 full texts were screened against the eligibility criteria. As a result, a final review sample of 164 records was identified, consisting of 163 empirical studies and one theoretical study. The entire process of identifying the review sample can be seen in Figure 6.

8.3.2.2 Identifying Sub-Sample for the Meta-Analysis

To gain insights into the effectiveness of TPACK-based interventions, we subsequently conducted a meta-analysis based on a sub-sample of the review sample. Given that self-reports have been discussed as sub-optimal measures of actual knowledge (e.g., Scherer et al., 2017), we only included studies that applied performance-based measures as proxy for teachers' competence to integrate technologies for teaching. At the same time, a first screening indicated that the type of research conducted in the field under scrutiny was rather diverse. Therefore, and to track possible knowledge growth, we only included studies that attained to a relatively strong research design such as pre-post designs, quasi-experimental designs, or designs that included a control group (see Evens et al., 2015, for a similar approach in the context of interventions fostering PCK). By applying these criteria, we obtained a final sub-sample for the meta-analysis of $n = 8$ studies, 7 of which applied a pretest-posttest design and one of which applied an experimental post-control group design.

Figure 6

Procedure According to the Prisma Framework



8.3.3 Coding Process

8.3.3.1 Coding Process for the Review

To answer Research Question 1, that is which TPACK-components were addressed in the interventions, we applied qualitative content analysis (Mayring, 2015). To do so, two raters screened the full texts, closely read the chapter where the design of the intervention was described and identified signal phrases, paragraphs or single words that clearly indicated whether there was explicit training or discussion on the respective TPACK-component (multiple coding). The raters based their decision on a pre-defined coding manual which comprised descriptions and eligibility criteria for each of the TPACK-components. The coding scheme contained rules and anchor examples for each of the seven TPACK-components (Appendix A).

After an initial mutual pilot coding phase (≈10% of the records), the two raters independently rated 20% of the remaining records to ensure the coding scheme's quality. The results yielded substantial interrater agreement, Cohen's $\kappa = .75$, (Landis & Koch, 1977) upon which one rater coded the remaining records with regard to targeted TPACK-components.

To explore possible links of contextual variables and TPACK-components, the raters screened each record and extracted information regarding context variables (i.e., participants' level of experience, subject domain and cultural background). Moreover, in case of empirical studys, the coders rated the measurement(s) used to assess TPCK. Here, we followed the prominent classification of TPCK-measurements into self-reports and performance-based measures, such as test-based questionnaire, evaluation of artefacts, observations (Koehler et al., 2012; Mouza, 2016; Voogt et al., 2013; Wang et al., 2018; Willermark, 2018). We coded any other measure, like open-ended questionnaires, reflective instruments and interviews, and subsumed them subsequently under "other measures". To explore possible trends over the years, we proceeded similarly to Huang et al. (2022) and divided the years of publication into three periods: Period 1 (years 2005 – 2010), period 2 (2011 – 2016), and period 3 (2017 – 2023).

8.3.3.2 Coding Procedure for the Meta-Analysis

We extracted all necessary information (sample sizes, means and standard deviations) provided in studies that allowed for effect size calculation. In some studies, the authors reported separate results for participants from different subjects (Koh et al., 2017; Koh, 2019) in which cases we averaged means and deviations and used this aggregated information for the subsequent data analysis. In cases in which TPCK was measured along several dimensions (Koh, 2019; Kramarski & Michalsky, 2009), we proceeded analogously.

8.3.4 Data Analysis

8.3.4.1 Systematic Review

To answer RQ 1 (i.e., the frequency of TPACK-components targeted in interventions), we calculated proportions of the targeted TPACK-components across all interventions.

To answer RQ 2 (i.e., dependence of TPACK-components across different contexts), we calculated several χ^2-tests with the respective TPACK-component and the respective context variables as categorical variables.

To answer RQ 3 (i.e., the co-occurrence of TPACK-components targeted in interventions), we calculated φ-coefficients to obtain information about the extent of co-occurrences between the respective TPACK-components.

8.3.4.2 Meta-Analysis

For the meta-analysis (RQ 4), we calculated Hedge's *g* as effect size measure of the individual studies based on the sample size, the sample means and the standard deviations of reported statistics. As we combined studies that applied different research designs (i.e., $n = 7$ included studies that applied pre-post design and $n = 1$ applied a post-control group design), we transformed effect sizes according to general recommendations (Borenstein et al., 2009, Cumming, 2013; Lakens, 2013; Morris & DeShon, 2002; see Appendix B for details on this transformation). We ran all statistical analysis with the sample comprising solely the pre-post studies first, before including the post-control group study by transforming the effect size conservatively. The entire procedure together with the exact formulas we used to obtain and transform effect sizes can be found in Appendix B.

To calculate an overall pooled effect size, we used the “metafor”-package in R (Viechtbauer, 2010) to fit a multilevel random-effects model in which effect-sizes were nested within studies. We used a random-effects model as it accounts for between-study heterogeneity and therefore seems reasonable given the diverse contexts of the included interventions (Borenstein et al, 2009). To account for the dependency of reported effect-sizes within one study (e.g., different outcome measures of the same sample group), we considered a multilevel structure to be appropriate (Harrer et al., 2022). To investigate heterogeneity in our data, we calculated the I^2-index (Higgins & Thompson, 2002) which is preferrable over Cochrane’s Q (Cochran, 1954) when the number of studies is limited (Harrer et al., 2022).

To explore whether the targeted TPACK-component affected the effectiveness of TPACK-based interventions, we further conducted a descriptive sub-group analyses for each T-component of TPACK. Accordingly, we fitted four different multilevel effects models (one for each T-component of TPACK: TK, TPK, TCK, TPCK) where we only included studies that targeted the respective T-component. This way, we could compare the pooled effect sizes between studies targeting different T-components on a descriptive level to get initial insights into whether the targeted TPACK-components might have influenced the effect of the interventions. We preferred this descriptive analysis over an inferential meta-regression due to the limited number of included studies in the meta-analysis sample (Borenstein, 2009).

8.4 Findings

The following findings are based on an analysis of the final data set provided in Table 2

Table 2

Complete Data Set of the Review Sample

	Context			Assessment strategy				Targeted TPACK-components						
Authors (year [a])	Region [b]	Subject domain [c]	Sample [d]	Meth.	Self-report	Perf.-based	Other	TK	PK	CK	TPK	TCK	PCK	TPCK
Açıkgül & Aslaner (2020)	AS	Mathematics	PST	qual.	1	1	1	0	0	1	0	1	1	1
*Agyei & Keengwe (2014)	AF	Mathematics	PST	mixed	1	1	0	1	1	0	0	1	0	1
Agyei & Voogt (2012)	AF	Mathematics	PST	qual.	1	0	1	1	1	0	0	1	0	1
Agyei & Voogt (2015)	AF	Mathematics	PST	mixed	1	1	0	1	0	0	1	1	1	1
Aktaş & Özmen (2022)	AS	Nat. sci.	PST	mixed	0	1	0	1	0	0	0	1	1	1
Aktaş & Özmen (2020)	AS	Nat. sci.	PST	qual.	0	1	0	1	0	0	0	1	1	1
Akyuz (2018)	AS	Mathematics	PST	mixed	1	1	0	1	1	1	0	1	0	1
Alabbasi (2018)	AS	Diverse	PST	mixed	1	1	0	1	0	1	0	1	1	1
Alayyar et al. (2012)	AS	Nat. sci.	IST	mixed	1	0	1	1	0	0	0	0	0	1
Alemdag et al. (2020)	AS	Language	T.Ed.	Mixed	0	1	1	1	1	0	1	0	0	1
Alrwaished et al. (2017)	AS	Mathematics	PST & IST	quant.	1	0	0	1	0	0	0	0	1	1
Alsofyani et al. (2012)	AS	Social	T.Ed.	quant.	0	0	0	1	1	0	1	0	0	0
Anat et al. (2020)	AS	Mathematics	PST	mixed	1	1	0	1	0	1	0	0	1	1

	Context			Assessment strategy				Targeted TPACK-components						
Authors (year [a])	Region [b]	Subject domain [c]	Sample [d]	Meth.	Self-report	Perf.-based	Other	TK	PK	CK	TPK	TCK	PCK	TPCK
Angeli & Ioannou (2015)	EU	Nat. sci.	IST	qual.	0	1	0	1	1	1	0	1	1	1
Ansyari (2015)	AS	Language	T.Ed.	Mixed	1	1	1	1	0	0	0	1	1	1
Antonenko (2013)	NA	Nat. sci.	IST	mixed	1	0	1	0	1	1	0	0	1	0
Araújo Filho & Gitirana (2022)	SA	Mathematics	PST	qual.	0	0	1	1	0	0	0	1	1	1
Arslan & Erdogan (2021)	AS	Nat. sci.	PST	mixed	1	0	1	1	0	0	0	0	1	0
Aşık et al. (2018)	AS	Language	PST	mixed	1	0	1	1	0	1	0	0	1	1
Aydogan-Yenmez & Gökçe (2017)	AS	Mathematics	PST	mixed	1	0	1	1	0	0	0	1	1	1
Banas & York (2014)	NA	Health education	PST	quant.	1	0	0	1	1	0	0	0	1	1
Belda-Medina & Calvo-Ferrer (2022)	EU	Diverse	PST	mixed	1	1	0	1	0	0	0	1	1	1
Beriswill et al. (2016)	NA	Social	IST	quant.	1	0	0	1	1	1	0	1	1	0
Blonder et al. (2013)	AS	Nat. sci.	IST	mixed	1	1	1	1	0	0	0	0	0	1
Blonder & Rap (2017)	AS	Nat. sci.	IST	mixed	1	0	1	1	0	1	1	0	0	0
Brush & Saye (2009)	NA	Social	PST	qual.	0	0	0	1	1	1	1	1	1	1
Bueno-Alastuey et al. (2018)	EU	Diverse	PST	mixed	1	1	1	0	1	1	0	0	1	1
Bustamante (2019)	EU	Language	IST	qual.	0	0	1	1	0	1	1	1	0	1

	Context			Assessment strategy				Targeted TPACK-components						
Authors (year [a])	Region [b]	Subject domain [c]	Sample [d]	Meth.	Self-report	Perf.-based	Other	TK	PK	CK	TPK	TCK	PCK	TPCK
Bustamante & Moeller (2013)	NA	Language	IST	qual.	0	1	1	1	1	1	1	1	0	1
Çalik et al. (2014)	AS	Nat. sci.	PST	quant.	0	0	0	1	0	1	0	1	0	1
Canbazoğlu Bilici (2016)	AS	Nat. sci.	IST	quant.	0	0	0	1	0	0	0	1	0	1
Canbazoğlu Bilici et al. (2016)	AS	Nat. sci.	PST	qual.	0	0	1	1	0	0	0	0	1	1
Casler-Failing (2021)	NA	Mathematics	PST	qual.	1	1	1	1	0	0	0	1	1	1
Cengiz (2014)	AS	Physical education	PST	quant.	1	0	0	1	0	1	1	0	1	1
Cetin-Dindar et al. (2018)	AS	Nat. sci.	PST	mixed	1	0	1	0	0	0	0	1	1	1
Chai et al. (2019)	AS	Diverse	PST	quant.	1	0	0	1	1	0	1	0	0	1
Chai & Koh (2017)	AS	Diverse	IST	quant.	1	0	0	1	1	0	1	0	0	1
Chai et al. (2010)	AS	Diverse	PST	quant.	1	0	0	1	1	0	1	0	0	0
Chai et al. (2011)	AS	Diverse	PST	quant.	1	0	0	1	1	0	1	0	1	0
Chew & Lim (2013)	AS	Mathematics	PST	quant.	1	0	0	1	0	1	0	1	1	1
Ciampa (2017)	NA	Diverse	IST	qual.	0	1	1	1	1	0	0	1	0	0
Crăciun (2019)	EU	Language	PST	quant.	1	0	0	1	1	1	1	0	1	1
Crosthwaite et al. (2021)	AS	Language	PST	qual.	0	1	0	1	0	0	0	1	1	1
Dalal et al. (2017)	NA	Diverse	IST	mixed	1	0	1	1	1	0	1	0	0	0
Dalal et al. (2021)	AS	Diverse	IST	mixed	1	1	0	1	1	0	1	1	0	1

	Context			Assessment strategy				Targeted TPACK-components					
Authors (year [a])	Region [b]	Subject domain [c]	Sample [d]	Meth.	Self-report	Perf.-based	Other	TK	PK	CK	TPK	TCK	PCK	TPCK
DeSantis (2013)	NA	Diverse	IST	mixed	1	0	0	1	0	0	1	0	0	0
Doering et al. (2009)	NA	Social	IST	mixed	1	0	1	1	0	1	1	1	1	1
Doering et al. (2014)	NA	Nat. sci.	IST	mixed	1	1	1	1	1	1	1	1	1	1
Durdu & Dag (2017)	AS	Mathematics	PST	mixed	1	0	1	1	0	0	1	1	0	1
Ergulec et al. (2021)	AS	X	PST	mixed	0	1	1	0	1	0	0	0	1	1
Ersoy et al. (2016)	AS	Language	PST	quant.	1	0	0	1	1	1	1	1	1	1
Eutsler (2021)	NA	X	PST	mixed	1	1	1	1	1	0	0	1	1	1
Fenton (2021)	NA	Nat. sci.	PST	mixed	1	0	1	0	0	1	0	1	1	1
George (2011)	X	Language	X	not emp.	0	0	0	1	0	1	1	1	0	1
Getenet et al. (2016)	AF	Mathematics	IST	mixed	1	1	1	0	0	0	0	0	1	1
Gokdas & Torun (2017)	AS	Diverse	PST	quant.	1	0	0	1	0	0	1	0	1	0
Gozukucuk & Gunbas (2022)	AS	X	PST	qual.	0	0	1	1	0	0	1	1	1	1
Graham et al. (2009)	NA	Nat. sci.	IST	mixed	1	0	1	1	0	1	0	1	1	1
Guerra et al. (2017)	EU	Nat. sci.	IST & T.Ed.	qual.	1	0	1	1	0	0	0	1	1	1
Guzey& Roehrig (2009)	NA	Nat. sci.	IST	mixed	1	0	1	1	1	1	1	0	1	1
Haciomeroglu et al. (2011)	NA	Mathematics	PST	qual.	0	1	0	1	0	0	0	1	1	1

	Context			Assessment strategy				Targeted TPACK-components						
Authors (year [a])	Region [b]	Subject domain [c]	Sample [d]	Meth.	Self-report	Perf.-based	Other	TK	PK	CK	TPK	TCK	PCK	TPCK
Hall (2018)	NA	Diverse	PST	mixed	1	1	0	1	0	0	1	0	0	0
Hammond et al. (2018)	NA	Nat. sci.	IST	mixed	1	0	1	1	0	1	0	1	1	1
Han et al. (2013)	AS	Diverse	PST	quant.	1	0	1	0	1	0	1	0	0	0
Hao (2016)	AS	Diverse	PST	mixed	1	0	1	1	1	1	0	0	0	1
Hardy (2010)	NA	Mathematics	PST	mixed	1	1	1	0	0	1	1	1	1	1
Harris & Hofer (2011)	NA	Social	IST	qual.	0	1	1	0	0	0	1	1	1	0
Holmes (2009)	AU	Mathematics	PST	qual.	0	1	1	1	1	1	1	0	1	1
Hong & Stonier (2015)	NA	Social	IST	qual.	0	0	0	1	1	1	0	1	0	1
Hosseini (2016)	AS	Diverse	PST	qual.	0	1	1	0	1	1	1	0	1	1
Hsu et al. (2015)	AS	Tourism	IST	mixed	1	0	0	1	0	1	1	1	0	1
I. Mustafa (2016)	NA	Nat. sci.	IST	mixed	0	1	1	0	1	1	0	1	1	1
Izgi-Onbasili et al. (2022)	AS	Diverse	PST	mixed	1	0	0	1	1	1	0	0	1	1
Jaipal-Jamani & Figg (2015)	NA	Nat. sci.	IST	qual.	0	1	1	1	0	0	1	0	1	1
Jang (2010)	AS	Nat. sci.	IST	qual.	0	1	1	1	0	1	0	0	1	1
Jang & Chen (2010)	AS	Mathematics	PST	qual.	0	1	1	1	0	1	0	0	1	1
Jimoyiannis (2010)	EU	Nat. sci.	T.Ed.	Qual.	0	0	1	1	0	0	0	1	1	1
Jimoyiannis et al. (2013)	EU	Diverse	IST	quant.	1	0	1	1	1	0	1	0	0	0
Jin & Harp (2020)	NA	Diverse	PST	mixed	1	0	0	1	0	0	1	0	0	0

	Context			Assessment strategy				Targeted TPACK-components						
Authors (year [a])	Region [b]	Subject domain [c]	Sample [d]	Meth.	Self-report	Perf.-based	Other	TK	PK	CK	TPK	TCK	PCK	TPCK
Jin & Schmidt-Crawford (2022)	NA	Diverse	PST	quant.	1	0	0	1	0	0	0	1	1	1
Kafyulilo et al. (2015)	AF	Nat. sci.	IST	mixed	1	0	1	1	1	0	1	0	0	0
Kapici & Akcay (2020)	AS	Nat. sci.	PST	mixed	1	1	0	1	0	0	0	1	1	1
Kartal & Dilek (2021)	AS	Nat. sci.	PST	quant.	1	0	0	1	0	0	0	1	1	1
Kayaalp et al. (2022)	AS	Social	PST	mixed	1	0	1	1	0	0	1	1	0	1
Ke & Hsu (2015)	NA	X	PST	mixed	1	1	1	1	0	0	1	1	0	0
Kersaint (2007)	NA	Mathematics	PST	qual.	0	1	0	1	0	0	0	1	1	1
Kharade & Peese (2014)	AS	Language	PST	mixed	1	1	1	0	1	0	0	0	1	1
*Koh (2019)	AS	Diverse	IST	mixed	1	1	0	1	1	0	1	0	1	1
Koh & Chai (2014)	AS	Diverse	IST	quant.	1	0	0	1	1	0	1	0	0	1
Koh & Divaharan (2011)	AS	Diverse	PST	qual.	0	0	1	1	0	0	1	0	0	0
Koh & Divaharan (2013)	AS	Diverse	PST	qual.	1	0	1	1	0	0	1	0	0	1
Koh, Woo & Lim. (2013)	AS	X	PST	quant.	1	0	1	1	0	0	1	0	0	0
*Koh et al. (2017)	AS	Mathematics	IST	mixed	1	1	0	0	1	0	0	0	1	1
Kohen & Kramarski (2012)	AS	Diverse	PST	mixed	1	1	0	0	1	0	1	0	0	0
Kong et al. (2020)	AS	Nat. sci.	IST	mixed	1	0	1	1	0	1	0	1	1	1

Authors (year [a])	Context			Assessment strategy				Targeted TPACK-components						
	Region [b]	Subject domain [c]	Sample [d]	Meth.	Self-report	Perf.-based	Other	TK	PK	CK	TPK	TCK	PCK	TPCK
*Kramarski & Michalsky (2009)	AS	Nat. sci.	PST	mixed	0	1	1	0	1	0	1	0	1	0
*Kramarski & Michalsky (2010)	AS	X	PST	mixed	0	1	1	1	1	0	1	0	0	0
*Lachner et al. (2021)	EU	Diverse	PST	quant.	1	1	0	0	0	0	1	0	1	1
Lee & James (2018)	AS	Language	IST	mixed	1	0	1	0	0	0	0	0	0	1
Lee & Kim (2014)	NA	Diverse	IST	mixed	0	1	0	1	0	0	1	1	0	1
Lee & Kim (2017)	NA	Diverse	PST	mixed	1	1	1	1	0	0	1	1	0	1
Lehtinen et al. (2016)	EU	Nat. sci.	PST	quant.	1	0	0	1	0	0	0	1	1	1
Liu & Kleinsasser (2015)	AS	Language	IST	quant.	1	0	1	1	1	0	1	0	1	1
Liu et al. (2015)	AS	Mathematics	PST & IST	qual.	0	1	1	0	0	0	1	0	0	0
Lu (2013)	NA	X	PST	qual.	0	0	1	1	0	0	1	0	0	0
Lyublinskaya & Du (2022)	NA	Diverse	PST	mixed	0	1	1	1	0	0	1	0	0	1
Lyublinskaya & Tournaki (2014)	NA	Mathematics	PST	mixed	1	0	0	1	0	0	1	0	1	1
Macrides & Angeli (2018)	EU	Music	PST	mixed	0	0	0	0	0	1	0	1	1	1
Maor (2016)	AU	Diverse	PST & IST	mixed	1	1	1	1	1	0	1	0	0	0
*Max et al. (2022)	EU	Nat. sci.	PST	quant.	1	1	0	0	0	0	0	1	1	1

	Context			Assessment strategy				Targeted TPACK-components					
Authors (year [a])	Region [b]	Subject domain [c]	Sample [d]	Meth.	Self-report	Perf.-based	Other	TK	PK	CK	TPK	TCK	PCK	TPCK
Meletiou-Mavrotheris & Prodromou (2016)	EU	Mathematics	PST	mixed	0	1	1	1	1	1	1	0	1	1
Miguel-Revilla et al. (2020)	EU	Social	PST	quant.	1	0	0	1	0	0	1	1	1	1
Mishra et al. (2019)	NA	Mathematics	IST	qual.	0	0	1	1	0	1	0	1	1	0
Morsink et al. (2011)	NA	Diverse	IST	mixed	1	1	1	1	0	0	0	0	0	1
Mourlam et al. (2021)	NA	Diverse	PST	quant.	1	0	0	0	1	0	1	0	0	0
Mouza & Karchmer-Klein (2013)	NA	Diverse	IST	qual.	1	1	0	1	1	0	1	1	1	1
Mouza et al. (2017)	NA	Diverse	PST	mixed	1	1	0	1	0	0	1	0	0	1
*Neumann et al. (2021)	NA	Diverse	PST	mixed	1	1	0	1	1	0	1	0	1	1
Nicholas & Ng (2012)	AU	Mechatronics	IST	qual.	0	0	1	1	0	1	0	1	0	0
Niess (2005)	NA	Mathematics	PST	qual.	0	0	0	1	0	1	1	1	1	1
Niess & Gillow-Wiles (2017)	NA	Diverse	IST	qual.	0	0	1	1	0	0	1	0	1	1
Niess et al. (2010)	NA	Mathematics	IST	mixed	0	1	1	0	0	0	0	1	0	1
Nilsson (2022)	EU	Nat. sci.	PST	qual.	0	0	1	0	1	1	0	1	1	1
Nilsson & Lund (2023)	EU	Nat. sci.	IST	qual.	0	0	1	1	0	0	0	1	1	1
Njiku et al. (2021)	AF	Mathematics	IST	quant.	1	0	0	0	0	0	0	1	1	1
Oakley (2020)	AU	X	PST	mixed	1	1	1	1	0	0	0	1	1	1

	Context			Assessment strategy				Targeted TPACK-components						
Authors (year [a])	Region [b]	Subject domain [c]	Sample [d]	Meth.	Self-report	Perf.-based	Other	TK	PK	CK	TPK	TCK	PCK	TPCK
Oda et al. (2020)	NA	Nat. sci.	IST	mixed	0	0	1	1	1	0	0	1	1	1
Önal & Alemdağ (2018)	AS	Diverse	PST	mixed	1	0	1	1	0	0	1	0	1	1
Özgün-Koca et al. (2010)	NA	Mathematics	PST	mixed	1	1	1	0	0	1	1	0	1	1
Özgür (2021)	AS	Diverse	IST	mixed	1	0	1	1	1	0	1	0	0	0
Özmantar et al. (2010)	AS	Mathematics	PST	mixed	0	1	1	1	0	1	0	1	1	1
Papanikolaou et al. (2017)	EU	X	PST	quant.	1	0	0	1	1	0	1	1	0	1
Peeraer & Van Petegem (2012)	AS	Diverse	T.Ed.	Mixed	1	0	1	0	0	0	1	0	0	1
Peng (2020)	NA	X	Ed.	Mixed	1	0	0	1	0	0	1	0	0	0
Pondee et al. (2021)	AS	Nat. sci.	PST	quant.	0	1	0	1	1	1	0	1	1	1
Price et al. (2014)	NA	Social	PST	mixed	1	1	1	0	0	0	1	1	1	1
Richardson (2009)	NA	Mathematics	IST	qual.	0	0	1	0	1	1	0	1	1	1
Rienties et al. (2013)	EU	X	T.Ed.	Quant.	1	0	0	1	0	0	1	0	0	1
Sancar-Tokmak (2013)	AS	Diverse	PST	qual.	0	0	1	1	1	0	1	0	0	1
Sancar-Tokmak (2015)	AS	Diverse	PST	qual.	0	0	1	1	1	0	1	0	0	1
Sancar-Tokmak et al. (2013)	AS	Diverse	PST	quant.	1	0	0	1	0	0	0	1	1	1
Sancar-Tokmak & Yanpar-Yelken (2015)	AS	Language	PST	mixed	1	0	1	1	0	0	0	1	1	1

	Context			Assessment strategy				Targeted TPACK-components						
Authors (year [a])	Region [b]	Subject domain [c]	Sample [d]	Meth.	Self-report	Perf.-based	Other	TK	PK	CK	TPK	TCK	PCK	TPCK
Sarhandi et al. (2016)	AS	Language	T.Ed.	Mixed	1	0	1	1	1	0	0	0	1	1
Sheffield et al. (2015)	AU	Nat. sci.	PST	mixed	1	1	0	1	0	0	1	0	1	1
Shinas et al. (2015)	NA	Diverse	PST	quant.	1	0	0	1	0	0	1	0	1	1
So & Kim (2009)	AS	Mathematics	PST	mixed	0	1	1	1	1	0	1	0	0	0
Sun et al. (2023)	AS	Nat. sci.	IST	mixed	1	1	0	1	0	1	0	1	1	1
Tai et al. (2015)	AS	Language	IST	mixed	1	1	1	1	0	0	0	0	1	1
Tee & Lee (2011)	AS	Diverse	IST	qual.	1	1	1	1	1	0	1	0	0	0
Tejada & Thayer (2019)	EU	Music	PST	quant.	1	1	1	1	1	1	0	1	1	1
Torun (2020)	AS	Social	PST	mixed	1	0	0	1	0	0	1	1	0	1
Tournaki & Lyublinskaya (2014)	NA	Mathematics	PST	quant.	1	0	0	1	0	0	1	1	0	1
Trautmann & Makinster (2009)	NA	Nat. sci.	IST	mixed	1	1	1	1	0	0	0	1	0	1
Tseng & Yeh (2019)	AS	Language	PST	mixed	1	1	1	0	0	0	0	1	1	1
Tseng et al. (2016)	AS	Language	IST	qual.	0	0	1	1	0	1	1	0	1	1
Tsouccas & Meletiou-Mavrotheris (2019)	EU	Mathematics	IST	mixed	0	1	1	1	0	1	0	1	1	1
Wang (2019)	AS	Tourism	T.Ed.	Quant.	1	0	0	0	1	0	0	1	0	1
Weisberg et al. (2022)	NA	Diverse	PST	qual.	0	1	0	1	1	0	1	0	1	1

Authors (year [a])	Context			Assessment strategy				Targeted TPACK-components						
	Region [b]	Subject domain [c]	Sample [d]	Meth.	Self-report	Perf.-based	Other	TK	PK	CK	TPK	TCK	PCK	TPCK
Wetzel et al. (2008)	NA	Social	PST	mixed	1	1	1	1	0	0	1	0	0	0
Wu et al. (2016)	AS	Diverse	IST	mixed	1	0	1	1	1	0	1	0	0	1
Xie et al. (2017)	NA	X	IST	mixed	1	0	1	1	1	1	0	0	0	0
Yildiz & Gokcek (2018)	AS	Mathematics	IST	qual.	0	0	1	0	0	0	0	1	1	1
You et al. (2021)	NA	Mathematics	IST	mixed	1	0	1	1	0	0	0	1	1	1
Zimmermann et al. (2021)	EU	Nat. sci.	PST	mixed	1	1	0	1	0	0	1	1	0	1
Total					109	83	95	132	63	51	83	84	98	129

Note. N = 163. For cells labelled with X, no information was provided in the respective studies.

[a] We used the year of the record's publication within a volume (as opposed to the record's first online publication date). Therefore, our sample included two studies from 2023, for example.

[b] AF = Africa, AS = Asia, AU = Australia, EU = Europe, NA = North America, SA = South America.

[c] Nat. sci. = Natural Sciences (i.e., biology, physics, chemistry). Diverse was coded when participants were from two different subject-domains (like natural science & languages)

[d] PST = Pre-service teachers, IST = In-service teachers, T.Ed. = Teacher educators.

* Included in the meta-analysis

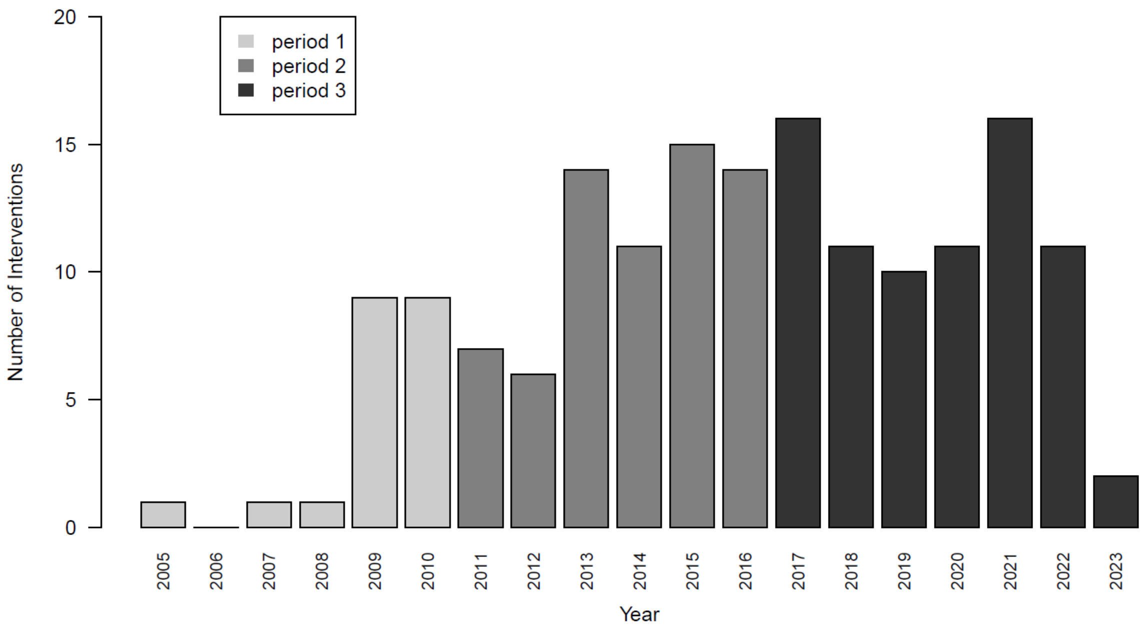
8.4.1 Preliminary Analysis

Geographical Location and Trends over Time

Most of the 163 empirical TPACK-based interventions were conducted in Asia (*n* = 77) and North America (*n* = 53) followed by Europe (*n* = 21), Africa (*n* = 6), Australia (*n* = 5), and South America (*n* = 1). Regarding potential trends over time, our findings indicate that the numbers of publications on TPACK-based interventions was fluctuating, but generally increasing (Figure 7).

Figure 7

Distribution of TPACK-Based Interventions by Years



Target Audience

Most TPACK-based interventions were provided for pre-service teachers only (*n* = 93; 57%), followed by in-service teachers only (*n* = 57; 35%) and studies that involved both participant groups (*n* = 4; 2%). Only nine interventions (5%) have been designed solely for teacher educators. In one study (Guerra et al., 2017), teacher educators worked together with in-service teachers.

Subject Domains of Participants

The majority of included studies (*n* = 37) were implemented for natural science teachers (i.e., biology, physics, geography or chemistry) followed by mathematics teachers (*n* = 34), language teachers (*n* = 17), and social science teachers (*n* = 11). Music education was the participants' subject in *n* = 2 studies, and physical education pertained to one study. In *n* = 3 studies, participants were from school unrelated subjects, such as tourism and leisure education or health education. In *n* = 46 studies, the participating teachers came from various subject-domain backgrounds (labelled "diverse" in Table 2). In *n* = 12 studies, the participants´ subject domain was not specified.

Methodological Approach

Out of the 163 empirical studies in our sample, *n* = 36 were quantitative, *n* = 42 qualitative, and *n* = 85 mixed-method studies.

Measures Used to Assess TPCK

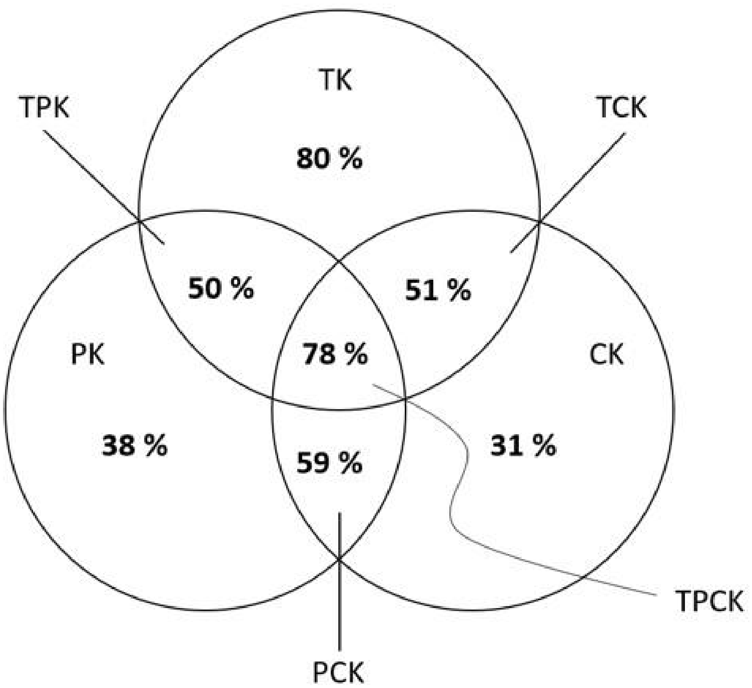
In *n* = 132 of the 163 included empirical studies, more than one data source was used to assess the interventions' effectiveness. Overall, the most common method used was self-reports (*n* = 109), a finding which is in line with previous research on TPACK (Koehler et al., 2012; Willermark, 2018). Performance-based measures, such as test-based instruments, the evaluation of design artifacts or observations were used in 83 studies. Other sources, like interviews, open ended questionnaires and reflective instruments (e.g., portfolios) were used to tap participants' TPCK in *n* = 95 interventions.

8.4.2 RQ 1: Which TPACK-Components Have Been Targeted in Previous TPACK-Based Interventions?

The entire distribution of the targeted components can be found in Figure 8. With 132 out of 164 interventions (80%), TK was the most prominent TPACK-component that has been targeted in previous TPACK-based interventions. The other first-order components PK and CK have been targeted in 63 (38%) and 51 (31%) of the interventions. Considering second-order TPACK-components, we found that PCK has been targeted in 98 (59%) of the interventions, followed by TCK (N = 84; 51%) and TPK (N = 83; 50%). TPCK, however, has only been targeted in 129 (78%) of the interventions which is surprising given that fostering TPCK is regarded to be the main aim of TPACK-based interventions.

Figure 8

Distribution of TPACK-Components Addressed in the Included Interventions



8.4.3 RQ 2: Do Contextual Variables Affect the Frequency of the Targeted TPACK-Components?

Next, we investigated whether the instructional contexts of the interventions affected the availability of the different targeted TPACK-components. The entire test statistics which the following results are based on can be found in Appendix C.

Regarding *trends over time*, we found an effect of time on TPK, $\chi^2(2) = 7.132$, $p = .028$. Looking at the numbers, we found that TPK was targeted less frequently in recent interventions (period 1: 57%, period 2: 61%, period 3: 39%) suggesting that researchers have shifted away from designing technology, subject-unspecific interventions. Similarly, we found an effect of time on CK, $\chi^2(2) = 7.635$, $p = .022$, which reflects a decline of interventions targeting CK from the early years onwards (period 1: 57%, period: 27%, period 3: 28%). None of the other tests was significant (see Appendix C).

Regarding the *target audience* (i.e., pre-service teachers vs. in-service teachers vs. educators) of previous interventions, we obtained a significant effect on CK, $\chi^2(2) = 6.461$, $p = .040$, as CK was only targeted in interventions for pre- and in-service teachers, but not for teacher educators. None of the other effects was significant. Given the small number of studies in our sample including teacher educators and hence possible inaccurate estimates in our χ^2-statistics (Agresti, 2007), we further investigated in a post-hoc analysis whether the level of experience (i.e., pre-service teachers vs in-service teachers and educators) effected the frequency of targeted TPACK-components. In this comparison, we found an effect of experience on PCK, χ^2 (1) = 3.868, $p = .049$. However, we found no effect of experience on any other TPACK-components (see Appendix C).

Regarding the *methodological approach* (i.e., quantitative, qualitative, mixed), our analysis revealed no significant effects (see Appendix C).

Regarding *regional patterns,* we similarly did not find an effect on the targeted TPACK-components. Given that most interventions took place in either North America or Asia (80% of all interventions), however, we conducted a post-hoc subgroup analysis based on studies that took place in these two regions. In this case, we found an effect of region (i.e., North America vs Asia) on TCK, χ^2 (1) = 4.807, p = .028: Whereas most interventions in North America have focused on TCK (58%), the majority of interventions located in Asia seemed to have considered training on TCK to a lesser extent (39%). No effect of region on any other targeted TPACK-component was significant (see Appendix C).

8.4.4 RQ 3: Which Combinations of TPACK-Components Have Been Targeted Together?

To explore combinations (i.e., co-occurrences) among the targeted TPACK-components, we calculated several φ-coefficients (see Table 3).

Table 3

φ-Correlations Among the Different TPACK-Components

TPACK-components	*n*	1	2	3	4	5	6	7
1. TK	132	1						
2. PK	64	−.05	1					
3. CK	51	−.03	.09	1				
4. PCK	98	−.15	−.14	.26*	1			
5. TPK	85	.13	.15	−.18	−.39**	1		
6. TCK	85	.01	−.26**	.18	.22*	−.40**	1	
7. TPCK	130	.01	−.17	.16	.39**	−.31**	.36**	1

Note. *p < .01, **p < .001 based on χ^2-tests with df = 1

Interestingly, although TK was the most frequently targeted TPACK-component, it was not significantly related to any other component. Furthermore, TPCK was positively related to PCK and TCK, indicating that subject-specific second order TPACK-components were prominently targeted together. In contrast, TPCK was negatively related to TPK, suggesting that researchers had the tendency to either foster subject-specific TPCK or generic TPK, but rarely both together.

8.4.5 RQ 4: How Effective Were Previous TPACK-Based Interventions?

Our final meta-analysis sample comprised seven pre-post studies and one post-control study published from 2009 to 2022. We obtained a total of 17 effect sizes. Six of them were based on measurement methods that estimated participants' knowledge of technology integration by test-based questionnaires. Ten effect sizes were based on measurements that involved the analysis of teaching artifacts (e.g., lesson-plans), and one effect size was based on the observation of teachers who implemented technologies in a live setting. Table 4 provides an overview of the included studies in our meta-analysis.

Table 4

Overview of the Included Studies in the Meta-Analysis

Study	Assessment			Effect size	
	N	Study design	Measure [a]	*g* [b]	*Var*
Agyei & Keengwe (2014)	8	Pre-post	2	1.225	0.217
	8	Pre-post	3	1.291	0.228
Koh (2019)	39	Pre-post	2	2.015	0.078
Koh et al. (2017)	7	Pre-post	2	1.635	0.342
Kramarski & Michalsky (2009)	45	Pre-post	1	0.948	0.032
	52	Pre-post	1	0.668	0.023
	47	Pre-post	1	2.094	0.068
	45	Pre-post	2	1.373	0.043
	52	Pre-post	2	0.695	0.024
	47	Pre-post	2	0.000	0.021
Kramarski & Michalsky (2009)	47	Pre-post	1	1.524	0.046
	47	Pre-post	2	1.315	0.040

	48	Pre-post	1	0.700	0.026
	48	Pre-post	2	0.849	0.028
Lachner et al. (2021)	208 [c]	Post-control	1	0.440 [d]	0.037
Max et al. (2022)	77	Pre-post	2	0.359	0.014
Neumann et al. (2021)	33	Pre-post	2	0.496	0.033

Note. [a] 1 = test-based measure, 2 = design-based measure, 3 = observation-based measure.

[b] Effect size estimates based on formulas provided in Appendix B.

[c] Reflects the total number of both the control and experimental groups combined.

[d] Here, we report the transformed effect size that corresponds to the most conservative estimate, $\rho = .5$, in equation (B.4).

Our multilevel random-effect model revealed a large average effect of TPACK-based interventions, g = .984. 95% CI [0.700, 1.268], p < .0001, suggesting that TPACK-based interventions were generally effective in fostering (pre-service) teachers' TPCK. The heterogeneity index I^2 = .89, however, was high indicating large overall heterogeneity of effect-sizes between the included studies.

As our meta-analysis was based on a restricted set of 17 effect sizes, we refrained from testing for potential moderators via inference statistics. Instead, we conducted descriptive analyses of subgroups (Table 5). The findings can be summarized as follows: In interventions that explicitly targeted TK, TPK, and TPCK, participants seemed to have improved their knowledge to teach with technologies the most. The effect sizes are large, and can be regarded to be meaningful, as zero was not included in the confidence intervals. At the same time, interventions targeting TCK seemed to have no meaningful effect, as zero was included in the confidence interval. Given the small number of included studies, however, these interpretations must be interpreted very cautiously.

Table 5

Sub-Group Analysis Based on Multilevel Random-Effects Models

Moderator		Effect size		95% CI	
	k	*g*	*SE*	Lower	Upper
TK	8	1.166	0.313	0.425	1.907
TPK	13	0.916	0.262	0.346	1.486
TCK	3	0.754	0.446	−1.166	2.673
TPCK	5	0.961	0.290	0.252	1.670

Note. CI = Confidence interval, *k* = number of effect sizes, *g* = Hedge's effect size, *SE* = standard error.

8.5 Discussion

The first overarching aim of our synthesis study was to synthesize prior TPACK-based interventions by a specific focus on knowledge integration, thereby extending prior studies that mostly focused on different aspects of the TPACK model like its measurement (e.g., Koehler et al., 2012) or its application in specific subject domains (e.g., sciences: Huang et al., 2022; languages: Tseng et al., 2020). To reach our first aim, we investigated which TPACK-components have been primarily targeted in TPACK-based interventions, and explored possible systematic patterns among targeted knowledge components considering several contextual variables to account for the context sensitivity of TPACK as demanded recently (Huang et al., 2022). The second aim of our study was to gain insights into preliminary evidence regarding effective TPACK-based interventions. Here, we explicitly relied on studies applying performance-based measures, such as test-based instruments or design-based evaluations, to infer robust evidence regarding the effectiveness of respective interventions. To our knowledge, our study is the first one that synthesizes evidence on TPACK-based interventions across the vast TPACK-landscape, allowing to draw legitimate conclusions regarding the effective implementation of the TPACK-model in practice.

8.5.1 Main Findings

8.5.1.1 Targeted TPACK-Components

Given the heterogenous distribution of targeted TPACK-components, we may conclude that researchers have designed interventions that were vastly diverse. In this sense, TPACK-based interventions did suffer from jangle-fallacies complicating the comparability of research findings among interventions. Regarding the frequency of targeted knowledge components of TPACK-based interventions (RQ 1), two main findings emerged from our analyses. First, the sheer mass of interventions targeting TK (80%) highlights the fact that researchers have considered TK an essential prerequisite for the acquisition of TPCK. This finding is interesting given that previous studies have found no or only a weak relationship between TK and TPCK (see Scherer et al., 2017, for an overview) which led researchers to conclude that a mere focus on TK-related training opportunities is not sufficient for the acquisition of teachers' TPCK (Schmid et al., 2020b). Second, only 80% of the interventions that aimed at targeting TPCK did actually offer specific training opportunities on TPCK. Conversely, in 20% of interventions, participants did not receive explicit training on TPCK. Consequently, after participating in such interventions, participants had to acquire TPCK "by their own". For instance, Wu et al. (2016) designed an ICT-module implemented for 162 in-service teachers. Though there was TPK-related instruction, such as the discussion on how to digitally evaluate students' learning outcomes, there was no direct link to the participants' subject domains, neglecting any subject-specific TPACK-components (i.e., CK, PCK and TPCK). Therefore, the participants had to apply and possibly adapt TPK to their specific subjects to become experts in technology integration for *specific subjects* (i.e., to acquire TPCK). Given that TPCK is subject-specific (Mishra & Koehler, 2006; von Kotzebue, 2022; Voogt et al., 2013), this may have posed severe challenges and it is an open question whether participants succeed in doing so without explicit training on TPCK. Examining this finding from a theoretical perspective, we may cautiously conclude that in 20% of TPACK-based interventions, TPCK was interpreted as integrative in nature as TPCK was not explicitly targeted. This is troubling given that recent empirical findings suggest that TPCK is transformative in nature (Schmid et al., 2020a), and hence, explicit support in acquiring TPCK seems mandatory for learning how to teach with technologies.

8.5.1.2 The Role of Context in the Design of TPACK-Based Interventions

Regarding the influence of contextual variables on the frequency of targeted TPACK-components (RQ 2), our findings revealed the following: Interventions in North American countries, like the USA or Canada, have targeted TCK significantly more often than interventions in Asian countries. This may be due to cultural differences. Possibly, pre-service education courses and professional developments in the USA or Canada have approached technology integration from a rather technocentric angle, whereas Asian countries emphasized the pedagogical side of TPCK.

Surprisingly, we only found limited evidence that interventions provided for pre-service teachers differed from those provided for in-service teachers or teacher educators, with PCK being the only TPACK-component targeted to varying extents across both groups. In particular, researchers have not appeared to adapt interventions with regard to explicitly targeting TPCK. This finding is alarming given that research on general expertise indicates that novices (i.e., pre-service teachers) need more support in integrating different knowledge structures than more experienced people like in-service teachers and teacher educators (Boshuizen & Schmidt, 1992; Linn, 2005).

8.5.1.3 Common Occurrences of Targeted TPACK-Components

Regarding the co-occurrences of different TPACK-components in interventions (RQ 3), we found the following patterns: First, the non-significant association of TK with the other TPACK-components indicate that technology-related skills (such as operating Power Point or spreadsheets) were unsystematically addressed across the included interventions. Second, the positive associations between CK, PCK, TCK, and TPCK suggest that TPCK has often been approached in a subject-specific manner, which is consistent with demands from previous research (e.g., Voogt et al., 2013). Third, the high negative association between TPK and TPCK indicates that researchers have rarely approached TPCK from a generic pedagogical angle which is interesting given that TPK has often been discussed as a requirement for TPCK (Lachner et al., 2019).

8.5.1.4 Effectiveness of TPACK-Based Interventions

Regarding the effectiveness of TPACK-based interventions (RQ 4), our findings suggest that interventions were generally effective in fostering TPCK, regardless of the specific TPACK-components that had been targeted. At the same time, our descriptive sub-group analyses indicate that there might have been slight differences after all. To elaborate, interventions targeting TK, TPK and TPCK seemed to have been most effective whereas interventions targeting TCK seemed to have been least effective in fostering technology integration. This may be interpreted as a promising result considering the prominence of interventions targeting TK. Possibly, the large effect of targeted TK on the acquisition of TPCK might have resulted from the fact that these interventions provided hands-on experience which improved participants' self-efficacy beliefs regarding technology integration; something that has been shown to be predictive of high-quality technology integration (Backfisch et al., 2020). Trying to translate these findings into practical implications, we may cautiously advise that interventions that aim at enhancing TPCK should specifically include opportunities for participants in which they acquire basic technological skills (i.e., TK). Yet, more meta-analyses on the effectiveness of interventions based on a larger sample are needed in the future. Having more studies at hand would allow for a comprehensive investigation of possible moderator effects via robust inferential methods like meta-regression (Borenstein et al., 2009). It would also be worthwhile to investigate whether certain combinations of TPACK-components moderate the effectiveness of interventions.

8.5.2 Theoretical Implications

Several theoretical implications arise from our findings. First, given the heterogenous distribution of targeted TPACK-components, we may conclude that researchers have designed interventions that were vastly diverse. In this sense, TPACK-based interventions did suffer from jangle-fallacies complicating the comparability of research findings among interventions. This is troublesome considering the prominence of TPACK as a foundation in the design and assessment of interventions.

Second, as TPCK was not explicitly targeted in 20% of the interventions, we may cautiously conclude that in these cases TPCK was interpreted as integrative in nature as participants would need to reach TPCK "on their own". This is troubling given that recent empirical findings suggest that TPCK is transformative in nature (Schmid et al., 2020, von Kotzebue, 2022), and hence, explicit support in acquiring TPCK seems mandatory for learning how to teach with technologies in subject-specific learning scenarios.

Third, regarding contextual influences on the design of interventions, our findings suggest that researchers have not comprehensively adapted their designs to specific contexts. For instance, there appears to be a lack of differentiation between the needs of less and more experienced participants (i.e., in-service teachers vs. pre-service teachers and teacher educators) as the targeted TPACK-components did not differ across respective interventions. This potential mismatch between what (pre-service) teachers need and what they receive warrants future research. Developing more adaptive interventions that consider these different needs could be a promising pathway to better support the development of technology-related professional knowledge – especially in interventions attended by both pre-service and in-service teachers.

8.5.3 Limitations

There are some limitations due to our methodological approach that need to be considered when interpreting our results. Though valuable in identifying targeted knowledge components in interventions in detail, our content analysis approach required rich textual information to to do so. Therefore, we had to exclude several records that lacked rich descriptions of the design of interventions, a procedure that may have resulted into a bias towards records that included detailed information on the design of the interventions. As a result, one needs to be cautious when generalizing our findings. Keeping that in mind, we want to encourage future researchers to clearly describe the design of interventions, a demand which has been brought forward by researchers before (Goldsmith et al., 2014; Thurm & Barzel, 2020).

Another concern relates to the exclusion of dissertations or grey literature which may have resulted in a distortion of our final results. However, due to the broad scope of our research (taking into account *any* TPACK-based intervention), including non-journal articles would have been unfeasible. Also, by including journal articles only, we could ensure a minimum of scientific quality in included studies.

Moreover, we only attained a limited number of studies for our meta-analysis which should prompt readers to interpret the results with caution. The limited sample size may be attributed to three factors. First, we used a sub-sample of our review sample for the meta-analysis. In line with our procedure, we first and foremost included studies that pertained to the first three research questions which we addressed by means of our systematic review. Possibly, this had led to the exclusion of numerous studies from the meta-analysis sample from the very beginning. Second, the low availability of performance-based measures likely contributed to the restricted sample, given that most of our included interventions applied self-reports, a finding which is in line with previous research (Koehler et al., 2012; Willermark, 2018; Wang et al., 2018). Our data even revealed a significant increase of self-report use over the years (period 1: 38%; period 2: 70%; period 3: 72%). This trend is worrying, provided that past research findings indicated that self-reports and performance-based measurements are only weakly related (Drummond & Sweeney, 2017; Kopcha et al., 2014; Max et al., 2022; So & Kim, 2009). Third, TPACK-based interventions have very rarely been investigated using designs that allow for inferences regarding their effectiveness. In particular, studies applying a control group were scarce in our sample. This is unfortunate as the predominant use of pre-post designs does not allow to draw causal conclusions regarding the effectiveness of the interventions, something that has been criticised in the context of TPACK-related studies before (Lachner et al., 2021).

Lastly, we did not consider other important contextual factors that could have accounted for differences in the effectiveness of interventions such as the duration of the intervention (see Desimone, 2009, for an overview of factors related to in-service teacher interventions, and Tondeur et al., 2012, for an overview of factors related to pre-service teacher interventions). However, we explicitly refrained from considering such factors due to the scope of our study (perspective on knowledge integration) and the lack of comparability of features across such diverse contexts.

8.5.4 Conclusion and Outlook

Overall, the empirical findings of this review confirm the sense of jangle-fallacies in the design of TPACK-based interventions. As such, our findings can be regarded as a plea for future researchers to carefully design and conceptualize TPACK-based interventions to make these interventions comparable across studies. Particularly, researchers should clearly describe which

TPACK-components are explicitly addressed in the course of the intervention, highlighting the connection between design choices and targeted knowledge domains. Relatedly, researchers should clearly indicate how contextual variables influence certain design choices they make.

Regarding future research possibilities, we advocate building upon our findings and delving more deeply into the question of how exactly TPACK-based interventions have been designed and orchestrated in the past. For example, investigating the specific order in which TPACK-components were targeted in interventions could be a promising path, as the sequence of instruction has been shown to impact the effectiveness of TPACK-based interventions (Hsu et al., 2015).

That said, to adequately model increases in competences, future research is needed which applies rigorous research designs in combination with performance-based assessments. Given the scarcity of studies taking such an approach, we encourage researchers to start focusing on the development of reliable test-based TPCK-measurements for specific subjects (Lachner et al., 2021; Max et al., 2022), and to apply them subsequently in robust research designs. These advancements will allow to make evidence-based recommendations for teacher education and help teachers acquire the required knowledge to effectively integrate technology in their teaching.

8.6 Appendix A

Coding Manual for Targeted TPACK-Components

This Appendix consists of the coding manual used to deduce which TPACK-components were targeted in each intervention. For each component, we provided two explicit anchor examples from the included studies. To help readers follow our manual, we provided rules for the inclusion of the respective TPACK-component as well as the exclusion of it. In the latter case, the arrow (→) indicates whether the rules would lead to the coding of another TPACK-component.

Table 6

Coding Manual for Targeted TPACK-Components

Targeted TPACK-component	Coding rules	Anchor examples
TK	*coded if* [a] • there was explicit training on how to operate specific technologies • there was detailed discussion on the use of specific technologies • participants of the intervention created a technological environment on their own with no specific relation to subjects (e.g. creating digital stories for primary students)	In Neumann et al. (2021), pre-service teachers were instructed on "how to use all aspects of Google Classroom from the teacher side" (p.1031) In Wu et al. (2016), teachers were introduced to Learning Management Systems, generic ICT systems and PowerPoint in the course of a ICT Training Module.

	not coded if • technologies were only introduced or discussed within a pedagogical or subject-specific context (→ TCK and TPK [b]) • no names of specific technologies were mentioned	In Jang (2010), science teachers should initially "become familiar with the implementation and functions of the hardware and software and reinforce the support in either hardware or software to prevent possible technical problems" (p. 1748).
PK	*coded if* • there was explicit training or discussion on how to write generic lesson plans • generic learning strategies, methods or pedagogical models were introduced or discussed *not coded if* • either of these pedagogical considerations were framed within a subject (→ PCK) or discussion of technology use (→ TPK)	In Ersoy et al. (2016), pre-service teachers were engaged in activities that involved the creating of lesson plans In Alsofyani et al. (2012), participants learned about Bloom's Taxonomy in a short blended online training workshop
CK	*coded if*	In Alabbasi (2018), within the course of a instructional technology program, pre-service

	• the participants received explicit training on a topic from a subject of their expertise (often either students or teachers of this specific subject) • participants were asked to choose one specific topic from their subject which they then used for further analyses / training sessions *not coded if* • if there was training on a specific topic (e.g., solar systems) but this topic did not match the participants' subject of expertise • if there is mentioning of different subject-related topics (such as vocabulary, reading, speaking etc.) but there is *no* explicit training that aims to facilitate participants' understanding of these topics. In other words: the knowledge of these topics was taken for granted by the instructor(s).	and in-service teachers had to design a digital storytelling activity. To do so, they first had to identify and analyse a content-related problem thoroughly. In Jang (2010), pre-service science teachers were asked to "describe his/her understanding of the subject-matter knowledge of the specific subject content unit in his/her journal" (p. 1748).
TPK	*coded if* • there was a training or discussion on how to use technologies for generic educational reasons (e. g.,	In Max et al. (2022), the participants of a media-based project including the work in a makerspace were first introduced to generic

	designing computer-based materials; computer-supported collaborative learning, etc.) • the participants had to develop lesson plans which included technologies used for generic teaching activities or teaching activities that were combined with a broad topic chosen only for the sake of the exercise. *Not coded if* • either of these criteria was met, *but only* in the context of a specific subject (→ TPCK)	media-based pedagogies such as the cognitive theory of multimedia learning. In Kohen and Kramarski (2012), teachers were asked to “develop a lesson design for high school students on the topic of smoking, in which you should integrate technology” (p. 5).
PCK	*coded if* • there was a general discussion on how to best teach and learn in the participants’ subject of expertise (Chai et al., 2011) • Participants were asked to discuss or develop lesson plans that included subject-specific topics and considerations of teaching or learning difficulties regarding the chosen topic. • There was general discussions or training on subject-specific pedagogies.	In Chai et al. (2011), pre-service teachers analysed “difficulties they perceived their students might face in understanding some concepts or theories in their subject-area” (p. 1188). In Kapici and Akcay (2020), pre-service science teachers were introduced to the inquire-based learning cycle.

	Not coded if • those subject-specific topics did not match the participants' subject of expertise, but they were only used for demonstration purposes • either of the above criteria was only met within the context of technology	
TCK	*coded if* • there was explicit training or discussions on how to operate specific technologies which are normally only used in specific subject domains (such as spreadsheets for mathematics, Google Earth for Geography or Video Editing Programmes specific for digital storytelling) • participants were asked to look for technologies of their academic subjects (Sancar-Tokmak, 2013) *not coded if* • either of the inclusion criteria was only met in the context of educational considerations (→ TPACK)	In Agyei & Voogt (2012), pre-service mathematics were introduced to basic spreadsheet functions for mathematical exploration. In Pondee et al. (2021), within a preservice science education course, pre-service teachers were introduced to a mobile game which visually represents blood cells and "enhances the understanding of the complex biological processes of the human body system" (p. 12).

TPCK	*coded if* • there was explicit consideration, training or discussion on how to combine TK, CK, and PK to foster students' learning. *Not coded if* • merely the framework TPACK was introduced without further exercises or discussions thereof. • any of the aforementioned categories matched.	

8.7 Appendix B

In this Appendix, we provide a detailed description for conducting our meta-analysis.

Estimating Effect Sizes

We calculated effect sizes of the individual studies based on the sample size, the sample means and the standard deviations of samples using the generic formula

$$d = \frac{m_{\text{diff}}}{s}, \tag{B.1}$$

where m_{diff} denotes the difference of two means (e.g., pre and post sample means in case of repeated measure design and the means of the independent groups in case of the control group design) and *s* an estimate of the standard deviation of the population under scrutiny, also called the standardizer of the effect size (Cumming, 2013). Given that from our final meta-analysis sample (n = 8) studies, one study (Lachner et al., 2021) used a different design, i.e., a post control group design, we had to transform effect sizes appropriately.

To combine effect sizes from different studies, it is important that effect sizes are standardized consistently across studies so that the metric used is comparable (Morris & DeShon, 2002). Given that only one study used a control group design, we followed general recommendations and first conducted a meta-analysis based on the seven studies that applied the same repeated measures design. Only then, in a second step, we included the control group study by combining effect sizes (see details below) from both the repeated measure studies and the one independent group study. If the inclusion of the control group study has no effect on the main results, we can conclude that our findings are robust.

Repeated Measure Designs

In cases of a repeated measure design, we averaged across the pre- and post-test sample deviation s_{pre} and s_{post} to obtain $s_{rm} = \sqrt{0.5 \cdot \left(s_{pre}^2 + s_{post}^2\right)}$ (the subscript *rm* reflecting the fact that we are dealing with repeated measure designs) as a standardizer which has been recommended when correlational information is missing (Borenstein et al., 2009; Cumming, 2013). To account for small study bias, we further used an approximation of Hedge's correction factor $J = 1 - \frac{3}{4df-1}$ (Borenstein et al., 2009), where df is the degrees of freedom of the standardizer, $df = N - 1$, where N denotes the sample size. Taken together, equation (1) translates to

$$d_{rm} = J \cdot \frac{m_2 - m_1}{\sqrt{0.5 \cdot \left(s_{pre}^2 + s_{post}^2\right)}}, \tag{B.2}$$

for repeated measure designs, where m_1 and m_2 are the means of the pre- and post-test respectively. To calculate an estimate for the variance of d_{rm} which is needed for providing precision estimates, we used the formula provided by Borenstein et al. (2009):

$$V = J^2 \cdot \left(\frac{2 + \mathrm{d}_{\mathrm{rm}}^2}{2\mathrm{N}}\right). \tag{B.3}$$

Combining Effect Sizes of Repeated and Independent Measure Designs

To include the control group study and to see whether our results are robust across different study designs, we needed to transform the effect size of the control group (i.e., independent measure design) to a similar metric used for our repeated measure designs. Given that repeated measure effect sizes (i.e., d_{rm}) are commonly larger than independent group design effects (Morris & DeShon, 2002), several authors proposed to correct for this bias using the correlation ρ between pre- and post-score (Borenstein et al., 2009; Cumming, 2013; Lakens, 2013; Morris & DeShon, 2002) as follows:

$$d_{rm} = \frac{d_{ig}}{\sqrt{2(1 - \rho)}}, \tag{B.4}$$

where d_{ig} refers to the effect size of the independent group design, which was reported by Lachner et al. (2021) 91erce .44. However, as none of the included repeated measure studies provided enough information to infer the correlation ρ between pre and post test measures, we conducted a sensitivity analysis (Borenstein et al., 2009) by using a range of plausible values for ρ in equation (4) to transform d_{ig} to d_{rm}. As within correlations are likely to exceed .5, we used steps of .1 to cover a conservative range for ρ from .5 to .9. For the variance of the transformed independent group effect, we used the median value of the variances of the repeated measure effect sizes as an approximation.

Pooling Effect Sizes

To calculate an overall pooled (or average) effect size, we fitted a multilevel random-effects model in which effect-sizes were nested within studies. We used a random-effects model as it accounts for between-study heterogeneity and therefore seems reasonable given the diversity of the included interventions' contexts (Borenstein et al, 2009). To account for the dependency of reported effect-sizes within one study (e.g., different outcome measures of the same sample group), we considered a multilevel structure to be appropriate (Harrer et al., 2022). For example, when data was reported that was based on different experimental groups who received similar input (e.g., Kramarski & Michalsky, 2009), we extracted relevant information for each group separately resulting in multiple dependent effect sizes within one study.

To investigate heterogeneity in our data, we calculated the I^2-index (Higgins & Thompson, 2002) which is preferable over Cochran's Q (Cochran, 1954) when the number of included studies is limited (Harrer et al., 2022).

To investigate whether heterogeneity between interventions' effectiveness is due to different knowledge foci (RQ 2), we specified a mixed-effects meta-regression model that included the different T-components of TPACK (i.e., TK, TPK, TCK, TPCK) as potential moderators.

8.8 Appendix C

Table 7

Technological Knowledge and Context Variables

Contextual variables	Technological Knowledge		
	Not targeted	Targeted	
Trend over time			$\chi^2(2) = 0.008$, $p = .931$
Period 1 (2005 – 2010)	5	16	
Period 2 (2011 – 2016)	11	56	
Period 3 (2017 – 2023)	16	60	
Region			$\chi^2(1) = 0.008$, $p = .931$
Asia	15	62	
North America	10	43	
Methodological approach			$\chi^2(2) = 0.834$, $p = .659$
Quantitative	6	30	
Qualitative	7	35	
Mixed	19	66	
Level of experience			$\chi^2(1) = 0.087$, $p = .767$
PSTs	19	74	
ISTs or Teach. Educ.	13	57	
Subject specificity			$\chi^2(1) = 0.863$, $p = .353$
Subject unspecific	10	53	
Subject specific	22	79	
Assessments			$\chi^2(1) = 0.028$, $p = .867$
No Self-reports	11	43	
Self-reports	21	88	

Table 8

Pedagogical Knowledge and Context Variables

Contextual variables	Pedagogical Knowledge		
	Not targeted	Targeted	
Trend over time			$\chi^2(2) = 2.126$, $p = .369$
Period 1 (2005 – 2010)	13	8	
Period 2 (2011– 2016)	37	30	
Period 3 (2017 – 2022)	51	25	
Region			$\chi^2(1) = 0.258$, $p = .612$
Asia	46	31	
North America	34	19	
Methodological Approach			$\chi^2(2) = 2.512$, $p = .285$
Quantitative	18	18	
Qualitative	27	15	
Mixed	55	30	
Level of experience			$\chi^2(1) = 0.916$, $p = .339$
PSTs	60	33	
ISTs or Teach. Educ.	40	30	
Subject specificity			$\chi^2(1) = 10.46$, $p = .001$
Subject unspecific	29	34	
Subject specific	72	29	
Assessments			$\chi^2(1) = 0.149$, $p = .700$
No Self-reports	32	22	
Self-reports	68	41	

Table 9

Content Knowledge and Context Variables

Contextual variables	Content Knowledge		
	Not targeted	Targeted	
Trend over time			$\chi^2(2) = 7.635, p = .022$
Period 1 (2005 – 2010)	9	12	
Period 2 (2011 – 2016)	49	18	
Period 3 (2017 – 2022)	55	21	
Region			$\chi^2(1) = 0.669, p = .413$
Asia	56	21	
North America	35	18	
Methodological approach			$\chi^2(2) = 2.297, p = .317$
Quantitative	28	8	
Qualitative	26	16	
Mixed	59	26	
Level of experience			$\chi^2(1) = 0.752, p = .386$
PSTs	67	26	
ISTs or Teach. Educ.	46	24	
Subject specificity			$\chi^2(1) = 11.066, p < .001$
Subject unspecific	53	10	
Subject specific	60	41	
Assessments			$\chi^2(1) = 3.848, p = .050$
No Self-reports	32	22	
Self-reports	81	28	

Table 10

Pedagogical Content Knowledge and Context Variables

Contextual variables	Pedagogical Knowledge	Content	
	Not targeted	Targeted	
Trend over time			$\chi^2(2) = 6.905, p = .032$
Period 1 (2005 – 2010)	6	15	
Period 2 (2011 – 2016)	35	32	
Period 3 (2017 – 2022)	25	51	
Region			$\chi^2(1) = 0.264, p = .607$
Asia	34	43	
North America	21	32	
Methodological approach			$\chi^2(2) = 1.916, p = .384$
Quantitative	15	21	
Qualitative	13	29	
Mixed	37	48	
Level of experience			$\chi^2(1) = 3.8682, p = .049$
PSTs	31	62	
ISTs or Teach. Educ.	34	36	
Subject specificity			$\chi^2(1) = 14.537, p < .001$
Subject unspecific	37	26	
Subject specific	29	72	
Assessments			$\chi^2(1) = 0.742, p = .389$
No Self-reports	19	35	
Self-reports	46	63	

Table 11

Technological Pedagogical Knowledge and Context Variables

Contextual variables	Technological Knowledge	Pedagogical	
	Not targeted	Targeted	
Trend over time			$\chi^2(2) = 7.132$ $p = .028$
Period 1 (2005 – 2010)	9	12	
Period 2 (2011– 2016)	26	41	
Period 3 (2017 – 2022)	46	30	
Region			$\chi^2(1) = 1.371$, $p = .242$
Asia	40	37	
North America	22	31	
Methodological Approach			$\chi^2(2) = 1.195$, $p = .550$
Quantitative	15	21	
Qualitative	22	20	
Mixed	44	41	
Level of experience			$\chi^2(1) = 1.035$, $p = .309$
PSTs	43	50	
ISTs or Teach. Educ.	38	32	
Subject specificity			$\chi^2(1) = 19.041$, $p < .001$
Subject unspecific	18	47	
Subject specific	63	38	
Assessments			$\chi^2(1) = 0.52$, $p = .471$
No Self-reports	29	25	
Self-reports	52	57	

Table 12

Technological Content Knowledge and Context Variables

Contextual variables	Technological Content Knowledge		
	Not targeted	Targeted	
Trend over time			$\chi^2(2) = 5.844$, $p = .054$
Period 1 (2005 – 2010)	10	11	
Period 2 (2011 – 2016)	40	27	
Period 3 (2017 – 2022)	30	46	
Region			$\chi^2(1) = 4.807$, $p = .028$
Asia	47	30	
North America	22	31	
Methodological Approach			$\chi^2(2) = 2.732$, $p = .255$
Quantitative	19	17	
Qualitative	16	26	
Mixed	45	40	
Level of experience			$\chi^2(1) = 0.042$, $p = .838$
PSTs	45	48	
ISTs or Teach. Educ.	35	35	
Subject specificity			$\chi^2(1) = 23.638$, $p < .001$
Subject unspecific	47	18	
Subject specific	34	67	
Assessments			$\chi^2(1) = 2.247$, $p = .134$
No Self-reports	22	32	
Self-reports	58	51	

Table 13

Technological Pedagogical Content Knowledge and Context Variables

Contextual variables	Technologial Pedagogical Content Knowledge		
	Not targeted	Targeted	
Trend over time			$\chi^2(2) = 2.69, p = .261$
Period 1 (2005 – 2010)	5	16	
Period 2 (2011 – 2016)	18	49	
Period 3 (2017 – 2022)	12	64	
Region			$\chi^2(1) = 0.978, p = .323$
Asia	16	61	
North America	15	39	
Methodological Approach			$\chi^2(2) = 0.417, p = .812$
Quantitative	9	27	
Qualitative	8	34	
Mixed	18	67	
Level of experience			$\chi^2(1) = 1.309, p = .253$
PSTs	17	76	
ISTs or Teach. Educ.	18	52	
Subject specificity			$\chi^2(1) = 17.1, p < .001$
Subject unspecific	25	40	
Subject specific	11	90	
Assessments			$\chi^2(1) = 0.058, p = .809$
No Self-reports	11	43	
Self-reports	24	85	

9 *Study 2*: Unraveling TPACK: Investigating the Inherent Structure of TPACK from a Subject-Specific Angle Using Test-Based Instruments

The content of this chapter has been published as an article in Computers & Education. Minor differences may still exist between this chapter and the final published version.

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Abstract

Against the backdrop of digitalization, it is imperative to provide pre-service teachers with adequate training opportunities to foster their professional knowledge regarding technology integration in teaching-learning scenarios. However, to date, only limited insights into the empirical nature of such knowledge – often subsumed under the term Technological Pedagogical and Content Knowledge (i.e., TPCK) – are possible given the heterogeneity of prior research investigating the empirical relationship between different knowledge components. This heterogeneity is likely due to the predominant use of self-reports in previous studies. Against this background, the present study pursued two goals. The first goal was to investigate the empirical nature of TPCK among pre-service teachers, utilizing test-based instruments to explore TPCK's nature from a subject-specific angle, that is, its relationship with Pedagogical Content Knowledge (PCK) and Technological Knowledge (TK). Given the widespread use of self-reports, the study's second goal was to examine the relationship between test-based and self-reported TPCK, exploring possible associated factors (e.g., pre-service teachers' gender, prior experience in teaching with technologies in school, or metacognitive accuracy) that may explain why both measures are linked only weakly. Findings reveal that both PCK and TK statistically predicted TPCK to a similar extent highlighting the integrated nature of TPCK. The relationship between test-based and self-reported TPCK was moderated by pre-service teachers' metacognitive accuracy, but not by their gender or prior experience. Together, these insights offer valuable guidance for refining teacher training regarding effective technology integration by indicating the need to target not only PCK and TK but also TPCK.

Keywords: TPACK, professional knowledge, technology integration, pre-service mathematics teachers, test-based instruments

9.1 Introduction

Integrating technology in the classroom has been shown to be a lever for supporting students' learning (see Hillmayr et al., 2020 for a meta-analysis in STEM). Empirical evidence indicated a positive relationship between teachers' professional knowledge and the quality of instruction (Backfisch et al., 2020), which is in turn closely related to students' learning outcomes as highlighted in a recent model by Lachner et al. (2024). Hence, teachers' professional knowledge is considered a crucial pre-requisite to integrate technologies effectively in subject-matter teaching (Clark-Wilson et al., 2020; Knezek & Christensen, 2016; Mishra & Koehler, 2006). In this light, it is imperative to take into account professional knowledge regarding technology integration early on in teachers' careers and develop adequate training opportunities for pre-service teachers. However, despite its relevance for both the design of effective pre-service teacher training (Fabian et al., 2024) and the design of adequate assessment strategies (Willermark, 2018), the precise empirical nature of such professional knowledge–commonly subsumed under the Technological Pedagogical and Content model (TPACK; Mishra & Koehler, 2006)–is largely unclear. This is because prior studies investigating the empirical relationships between different knowledge components have produced mixed results. For example, to date, it is debated whether Technological Pedagogical Content Knowledge (i.e., TPCK[8]) as the central knowledge component of TPACK is a related

[8] Note that in the present paper, we follow Schmid et al. (2020) and use the term TPACK when referring to the TPACK model as a whole (including all of its seven knowledge components, i.e., TK, PK, CK, TPK, TCK, PCK, & TPCK). Instead, we use TPCK when explicitly referring to the specific knowledge component within the TPACK model.

but distinct knowledge component from Pedagogical Content Knowledge (PCK; Shulman, 1986) or merely a sub-facet of it (Große-Heilmann et al., 2022; Schubatzky et al., 2023). The inconsistencies of prior studies on the empirical relationships of TPACK-components may have arisen as most empirical studies predominantly relied on self-report instruments to measure these components (Koehler et al., 2011 ; Willermark, 2018). Although ecologically reasonable and valuable in providing initial proxies for knowledge, self-reports require participants to assess their knowledge accurately, a process that has been shown to introduce potential biases in the level of TPCK concerning different variables, such as gender (Gómez-Trigueros and Yáñez de Aldecoa, 2021; Koh et al., 2010) or pre-service teachers' experience (e.g., Heine et al., 2023; Jang & Tsai, 2012). Therefore, it is commonly agreed upon that self-reports present a sub-optimal way to assess TPACK (Lachner et al., 2019; Scherer et al., 2017). Despite the widespread use of self-reports in the TPACK literature, little research has been conducted to explore empirically why the relationship between self-reported and test-based TPCK is commonly weak (Drummond & Sweeney, 2017; von Kotzebue, 2022). Together, the review of the literature has shown two interrelated desiderates pertaining to the TPACK ecosystem. First, the inherent empirical nature of TPACK has remained largely unclear. Second, it is an open question why self-reported and test-based TPCK are commonly linked weakly. In the present study, we sought to shed light onto these two desiderates. Accordingly, we explored the inherent empirical nature of TPACK within pre-service teachers, using test-based instruments, and investigated its relationship to TK and PCK. Given the relevance of PCK for high teaching quality (Baumert et al., 2010), as well as the subject-specific nature of TPACK (Max et al., 2022; von Kotzebue, 2022; Voogt et al., 2013) and its context-sensitivity (Mishra, 2019), we employed the study in the context of mathematics education. Specifically, we examined whether the distinction between mathematics-specific TPCK and mathematics-specific PCK drawn by Mishra and Koehler (2006) is empirically warranted (see Krauss. et al., 2008, for related approaches on the relationship of PCK and CK). Moreover, we examined the relationship between self-reported and test-based TPCK and explored possible boundary conditions on this relationship, such as pre-service teachers' gender, prior experience, and metacognitive accuracy (i.e., ability to accurately self-asses one's knowledge).

9.2 Theoretical Background

9.2.1 Pre-Service Teachers' Professional Knowledge for Technology Integration

Integrating technologies during subject-specific instruction requires rich knowledge of how to exploit the affordances of technologies to support students' learning (Knezek & Christensen, 2016; Mishra & Koehler, 2006). Considering the importance of future teaching with technologies, much research has been put into conceptualizing such knowledge. The TPACK model introduced by Mishra and Koehler (2006) as an extension of Shulman 's Pedagogical Content and Knowledge framework is one of the most prominent conceptualizations of professional knowledge (Brianza et al., 2023; Hew et al., 2019; Schmid et al., 2024). As such, it has been discussed as a "highly relevant and useful framework for informing educational research and practice" (Schmid et al., 2024, p. 14). Therefore, TPACK was used as the guiding framework in the present study. The TPACK model suggests that the central knowledge for subject-specific technology-enhanced teaching–i.e., Technological Pedagogical Content Knowledge (TPCK)–emerges from the complex interplay of basic knowledge components such as PCK and TK. PCK relates to knowledge about how to foster students' subject-specific learning best, including knowledge about their (mis-) conceptions of relevant content-related topics and how to adapt teaching strategies to students' individual needs to support their acquisition of conceptual knowledge best (Shulman, 1986). PCK has been discussed to be a central knowledge for the profession of teaching (Shulman, 1986) and predictive of high-quality instruction especially in the context of mathematics (Backfisch et al., 2020; Baumert et al., 2010; Blömeke & Kaiser, 2014). Technological Knowledge (TK) refers to knowledge of technologies that, for instance, includes knowledge about operating with digital technologies comprising “standard sets of software tools such as word processors, spreadsheets, browsers, and e-mail” (Mishra & Koehler, 2006, p. 1027). In the ongoing digital transformation, TK has been considered crucial for implementing technologies into subject-matter teaching and learning (Fütterer et al., 2023; Kastorff et al., 2022).

9.2.2 The Inherent Structure of TPACK

9.2.2.1 Theoretical Considerations

A vivid debate on the theoretical nature of TPCK (i.e., the central TPACK-component) evolved which concerned the question of how TPCK is developed during pre-service teacher training (Angeli & Valanides, 2009), and ultimately how TPCK is related to the other TPACK-components (Schmid et al., 2020). Two opposing views crystallized around these questions: The integrative and transformative views (Angeli & Valanides, 2009). According to the integrative view, TPCK is not a distinct or unique body of knowledge. Instead, TPCK is closely related to all of the other TPACK-components (i.e., TK, PK, CK, PCK, TCK, and TPK). Therefore, high levels of TPCK should correspond to high levels of all other TPACK-components including PCK and TK (Schmid et al., 2020; von Kotzebue, 2022). In contrast, the transformative view posits TPCK as a distinct and unique knowledge component that goes “beyond simple integration, or accumulation, of the constituent knowledge bases” (Angeli & Valanides, 2009, p. 158). In this view, teachers’ TPCK is shaped by the second-order components (e.g., PCK) but not directly by the first-order components such as TK (Schmid et al., 2020; von Kotzebue, 2022). Therefore, TPCK should be more closely related to PCK than to TK. These unclear theoretical underpinnings may have shaped how researchers from different disciplines conceptualized TPCK regarding its relationship to other TPACK-components. For example, whereas some researchers have conceptualized TPCK as a unique knowledge facet (e.g., Angeli & Valanides, 2009), others considered TPCK to be a sub-facet of PCK (Große-Heilmann et al., 2022; Schubatzky et al., 2023). These different conceptualizations should be reflected in the empirical relationships of TPCK with PCK and TK: If TPCK was merely a sub-facet of PCK, it may be reasonable to suggest that TPCK and PCK are empirically very closely related. At the same time, as TK refers to knowledge theoretically distinct from PCK (Mishra & Koehler, 2006), assuming a lower relationship between TPCK and TK may be reasonable.

9.2.2.2 Empirical Studies on the Relationships Between TPCK, PCK, and TK

Numerous studies have aimed to empirically clarify the inherent structure of TPACK to shed light on the ongoing debate regarding its inherent structure and inform practice in designing effective training opportunities for pre-service teachers. Considering the relevance of PCK and TK for effective technology integration, the relationships between TPCK, PCK, and TK have been studied extensively. However, empirical findings on the relationships of these TPACK-components were mixed. On the one hand, studies provided evidence that TPCK is statistically influenced by PCK but not by TK (Pamuk et al., 2015; Schmid et al., 2020). On the other hand, Koh et al. (2013)found that TPCK was influenced by TK but not PCK. Other studies indicated that neither PCK nor TK statistically influences TPCK (Dong et al., 2015). Possibly, this heterogeneity arises as most studies relied on self-report measures in which participants need to assess their level of knowledge, a procedure which has been considered limited in assessing objective TPCK (Fütterer et al., 2023; Lachner et al., 2021; Willermark, 2018). Reasons for the limitations of self-reports have been prominently discussed in the past (Lachner et al., 2021 ; Schubatzky et al., 2023; von Kotzebue, 2022; Voogt et al., 2013) and encompass induced bias arising from social desirability or the challenge individuals face in accurately assessing their knowledge (Maderick et al., 2016; Urhahne & Wijnia, 2021). Especially beginners struggle to accurately assess their knowledge (Kruger & Dunning, 1999). Therefore, self-reports are valuable for providing proxies for the level of TPCK but they are not the optimal way to assess objective TPCK (see Lachner et al., 2021 , for a thorough discussion on self-reports in the context of TPACK research). In contrast, test-based instruments have been considered superior over self-reports in assessing knowledge as they provide objective, quantifiable measures of what individuals know or can do, reducing the subjectivity and bias inherent in self-reports. Moreover, test-based assessments can be systematically standardized and validated, ensuring reliability and comparability across different contexts and populations. Given these advantages, researchers started developing and employing test-based instruments to explore the structure of TPACK from a more cognitive angle (Baier & Kunter, 2020). Most of these studies concentrated merely on subcomponents of the TPACK model, such as technology-unrelated PCK (Kilian et al., 2021; Krauss et al., 2008) or subject-unspecific TPK (Baier & Kunter, 2020; Lachner et al., 2019) and therefore did not provide insights into the relationship of TPCK with other TPACK-components. In particular, studies on the relationship between TPCK and PCK are lacking. This is surprising given the central role of PCK in the teacher profession (Baumert et al., 2010; Shulman, 1986). A scarce example applying a test-based TPCK instrument was provided by von Kotzebue (2022) who investigated the relationship between TPCK, TPK, and TCK within a study implemented for 206 biology pre-service teachers. The author developed a new instrument to measure biology-specific TPCK which included the use of text-based vignettes depicting common teaching scenarios in biology classes. This TPCK test was employed together with test-based measures for each of the other T-components of the TPACK model which included–next to TK and TPK–Technological Content Knowledge (i.e., TCK), that is knowledge about technologies used in specific domains regardless of pedagogical applications (Mishra & Koehler, 2006). On the one hand, the results suggested that TPCK is more closely related to TPK ($r = 0.50$) than it is to TK ($r = 0.34$). On the other hand, TCK yielded a non-statistically significant relationship with TPCK ($r = 0.01$). Moreover, the results of a subsequent structural equation modeling in which TK, TPK, and TCK were specified as predictors for TPCK revealed that both TPK and TCK predicted TPCK, but TK did not. These findings were supportive of the transformative view of TPACK given the somewhat closer relationship of the second-order TPACK-components (i.e., TPK and TCK) compared to first-order TK. Moreover, the predictive power of TPK on TPCK was stronger ($\beta = 0.29$) than the predictive power of TCK on TPCK ($\beta = 0.69$), suggesting that TPK and TPCK are stronger related than TCK and TPCK. In light of the critical role of PCK in teacher education (Krauss et al., 2008) and its important role in predicting student achievement (Baumert & Kunter, 2013), the question arises where PCK would fit in. To date, there has been no research on the relationship between test-based PCK and test-based TPCK using similar models, leaving the question of the predictive power of PCK on TPCK and the empirical distinguishability of both subject-specific components unresolved.

9.2.3 The Relationship Between Test-Based and Self-Reported TPCK

A As illustrated above, findings on the empirical relationship between TPCK and different TPACK-components were mixed, likely due to the distortions induced by self-report measures. Although used frequently for estimating the effectiveness of technology-related interventions (Fabian et al., 2024; Willermark, 2018), or for supporting pre-service teachers in acquiring respective knowledge (Max et al., 2022), little research has been put into comparing test-based and self-report instruments assessing TPCK (see Kastorff et al., 2022, for comparing test-based and self-reported TK). A rare exception was provided by the study of von Kotzebue (2022) who compared pre-service teachers' test-based TPCK with their self-reported TPCK. She found that both measures were linked weakly ($r = 0.09$). Similar studies regarding the relationship of test-based and self-reported TPCK measures found somewhat stronger, yet still comparatively small correlations. For example, Drummond and Sweeney (2017) developed a performance-based measure including true/false items and investigated the relationship to self-reported TPCK (Kabakci Yurdakul et al., 2012). Based on a sample of 93 pre-service teachers, the correlation was small ($r = 0.24$). However, the items used to assess TPCK were rather generic in nature and did not seem to draw upon any subject-specific knowledge (e.g., “Research suggests that technology generally motivates students to participate in the teaching and learning process”; Drummond & Sweeney, 2017, p. 935). Relatedly, another study by Baier and Kunter (2020) yielded a similar weak correlation between self-reported and performance-based knowledge assessments in the context of TPK (r = 0.15). In sum, previous research suggests that test-based and self-reported TPCK were only related to a limited extent, a finding which urgently needs further inspection given the widespread use of self-report measures across the TPACK landscape (Koehler et al., 2011; Willermark, 2018). To date, little attention has been brought to investigating possible explanations for the low correspondence of both measures which was exactly the second goal of the present study.

9.2.3.1 Variables Affecting the Relationship Between Test-Based and Self-Reported TPCK

Gender. To examine why test-based and self-reported TPCK are empirically linked only weakly, we included three variables which might affect this relationship: gender, prior experience and metacognitive accuracy. We specifically focused on these three variables given that those have been discussed to be associated with (pre-service) teachers’ self-reported TPACK-components in prior studies (gender: Koh et al., 2010; prior experience: Heine et al., 2023; metacognitive accuracy: Abbitt, 2011) and have been discussed extensively in the TPACK literature. Gender. Early research on computer use documented that there were decisive gender differences in favor of male teachers when it comes to attitudes regarding pre-service teachers’ attitudes or use of computers detached from any pedagogical context (Kay, 2006). With the advent of technologies in classrooms, researchers started to investigate whether similar results translate to TPACK-related research. However, previous research findings in the field of TPACK were inconclusive: On the one hand, several studies could not replicate the gender differences of computer usage in the field of TPACK (Jang & Tsai, 2012; Koh & Chai, 2011). On the other hand, there is growing evidence that males tend to rate their TPCK higher than females. For example, Koh et al. (2010) investigated potential gender differences among a sample of 1185 pre-service teachers and found that men rated their knowledge of teaching with technology significantly higher than females. Relatedly, Gómez-Trigueros and Yáñez de Aldecoa (2021) found similar gender effects on self-reported TPCK based on an analysis of 914 pre-service teachers from Spanish universities. Whether these findings translate to objective TPCK remains an open question.

Prior Experience. Previous studies have shown that integrated knowledge domains such as PCK (Krauss et al., 2008) or TPK (Heine et al., 2023; Lachner et al., 2019) are sensitive to pre-service teachers' level of experience (cf. knowledge encapsulation, see Boshuizen & Schmidt, 1992). Tondeur et al. (2012) also highlighted the crucial role of authentic experiences with technology integration for the development of pre-service teachers' TPCK: "It seems to be important that pre-service teachers have the possibility to see and experience the pedagogical integration of technology in the classroom during their training experiences, by observing good examples and being able to implement such practices themselves" (p. 9). In this light, pre-service teachers who had previous experience of teaching in schools (e.g., during a practical internship) should be able to outperform those in TPCK who did not. It seems worthwhile to investigate whether TPCK–as the integration of PCK and TK–also depends on (pre-service) teachers' level of experience.

Metacognitive Accuracy. Metacognitive accuracy is a term coined within the research field of metacognition (Flavell, 1979) which describes the ability of people to assess their own knowledge accurately (Maki & McGuire, 2002). Metacognitive accuracy is often conceptualized as the extent of deviation between a person's believed/self-judged skill and his/her actual level of skill or performance. It is most commonly operationalized as the squared difference between both measures: $(X_{Performance} - X_{Judgement})^2$ (Schraw, 2009). An extensive body of evidence exists that (pre-service) teachers struggle to accurately judge their own knowledge regarding technology integration (Fütterer et al., 2023; Maderick et al., 2016; Max et al., 2022).

Given that answering self-report TPCK questions requires participants to assess their own knowledge, it seems reasonable to assume that the gap between test-based and self-report TPCK measures depends on participants' level of metacognitive accuracy. For example, Abbitt (2011) argued as follows: "As with any self-reporting measure, the ability of the instrument to accurately represent knowledge in the TPACK domains is limited by the ability of the respondents to assess their own knowledge and respond appropriately to the survey items" (p. 291). Following the author's argumentation, the better people are able to accurately assess their own knowledge (i.e., the less deviation there is between judged and actual level of skill), the more their self-reported and test-based TPCK scores should be correlated.

9.2.4 The Present Study

The two overarching goals of the present study were (1) to shed light on the empirical inherent structure of TPCK from a subject-specific angle using test-based instruments, and (2) to investigate possible boundary conditions on the relationship between test-based and self-reported TPCK.

Regarding the first goal, we specifically examined whether the theoretical distinction between PCK and TPCK drawn by Mishra and Koehler (2006) could be empirically justified. Contrasting these findings with relationships between TK and TPCK results could yield important insights into the ongoing debate on the theoretical underpinnings of TPCK as either transformative or integrative, and the thoughtful implementation of the TPACK model for the design of effective pre-service teacher training. We formulated the following two pre-registered research questions tackling our first goal:

(RQ 1a) What are the empirical relationships between TPCK, PCK, and TK of pre-service mathematics teachers assessed by subject-specific, test-based measures?

(RQ 1b) What is the predictive power of PCK and TK on TPCK and do these predictions support the transformative or integrative view of TPCK?

Given the widespread use of self-reports in the TPACK landscape, we investigated to what extent our subject specific TPCK measure was related to self-reported TPCK. As findings from prior research were rather diverse (see 2.3), we examined possible boundary conditions on this relationship. As a result, the research questions tackling the second overarching goal were as follows :

(RQ 2a) What is the relationship between test-based and self-reported TPCK within pre-service teachers?

(RQ 2b) Is this relationship affected by gender, prior experience, or the metacognitive accuracy of pre-service teachers' self-assessed level of TPCK?

9.3 Method

9.3.1 Design and Sample

We employed a cross-sectional online study with secondary mathematics pre-service teachers from a total of ten different German universities. The study was conducted from March 2022 to February 2023. In Germany, pre-service teachers are obliged to study at least two content-related subjects (e.g., Mathematics and English) besides taking courses that aim at fostering specific teaching relevant knowledge, such as PCK. Another peculiarity of the pre-service teacher training curriculum in Germany is that at some point during their training, pre-service teachers are required to spend a practical internship in schools teaching mathematics, often for the first time. Participants were selected through self-selection sampling which is a non-probability sampling technique where participants volunteer in response to an invitation, based on specific criteria (here, being pre-service mathematics teachers; see 3.3. for details on the selection process). In total, we obtained data from 150 pre-service mathematics teachers.2 As preregistered, we eliminated 8 participants from the dataset, who finished the survey in less than 15 min (which corresponds to less than 50% of the average time participants needed to answer the knowledge tests). Further, we eliminated data from one participant who did not answer each of the test-based TPCK item presented to him/her. Therefore, our final sample included data from N = 141 pre-service teachers (100 females & 41 males) who were trained to teach mathematics in German upper secondary schools. On average, they were 21.5 years old (SD = 2.17) and either in the Bachelor's (n = 108) or Master's program (n = 33). To keep the survey parsimonious and to avoid fatiguing effects, we implemented a planned missing data design (Graham et al., 2006). Accordingly, the pre-service teachers randomly received only some, but not all items for each of the test-based instruments (see details in the following).

9.3.2 Instruments

We used previously validated instruments to measure TPCK, PCK, and TK. Each construct had been demonstrated to be one dimensional in previous studies (test-based TPCK: Lachner et al., 2021; PCK: Buchholtz et al., 2016; TK: Fütterer et al., 2023). Given that we adapted some instruments, we initially fitted a one-dimensional model for each of our test-based constructs (i.e., test-based TPCK, PCK, TK) using Confirmatory Factor Analyses (CFA), in which the constructs were represented as the only latent variable in the respective models. After establishing one-dimensionality, we transformed the raw scores of test-based TPCK, PCK, and TK by calculating estimates for the person ability as detailed in the following.

9.3.2.1 Test-Based Instruments

Mathematics-Specific Technological Pedagogical Content Knowledge (TPCK)

To measure TPCK, we adapted the mathematics version of the test instrument developed by Lachner et al. (2021). The test-based TPCK instrument comprised eight items and was based on open-ended items that contained text vignettes that depicted typical math-specific teaching problems in the classroom (e.g., “The Pythagorean theorem is often misused in exercises in your ninth-grade class, which can be attributed to possible misconceptions about the theorem. For example, the theorem is frequently applied to triangles without a right angle, or the formula is memorized without understanding its geometric relationship. How could you use educational technologies to help your students develop a better understanding of the Pythagorean theorem and consequently apply it correctly? Please justify your answer."). From the original test used by Lachner et al. (2021), we replaced three items to ensure content validity by having the items cover the whole range of topics in the curriculum of upper secondary schools. The one-dimensional CFA indicated good fit to our data (Root Mean Square Error of Approximation [RMSEA] < 0.001; Standardized Root Mean Square Residual [SRMR] = 0.068, Robust Comparative Fit Index [CFI] = 1.000). As the study by Lachner et al. (2021) was an effectiveness study and did not focus on the validity of the instrument, we also ensured that our TPCK instrument was reliable and valid by piloting the instrument beforehand. In this pilot study, 16 pre-service teachers answered all eight items at two distinct measurement points spaced one week apart. To account for remembering effects, we randomized the order of the test-based TPCK items at the second measurement point. To establish (test-retest) reliability, we calculated the correlation between both measurement points, which was high, $r = 0.72$. To establish validity, we investigated the convergent validity by comparing the test-based TPCK scores with the instructional quality of lesson plans (scenario adapted by Backfisch et al., 2020) provided by the pre-service teachers at the second measurement point. Again, the correlation between both measures was high, $r = 0.64$, which demonstrated the external validity of our instrument (Schmidt-Atzert & Amelang, 2012). Of the eight test-based TPCK items, participants randomly received five of them. To account for the intended missing values, we employed a Full Information Maximum Likelihood (FIML) method as recommended (Graham, 2012). For each item, pre-service teachers could receive 0 to 3 points (see https://osf.io/y9hxt/ for the coding manual). To ensure coding quality, two raters coded 20% of all open test-based TPCK answers independently. Since interrater reliability was good (ICC = 0.91), the items were split in half and each rater coded the rest of the answers of their respective items independently.

For the subsequent analysis, we estimated participants' test-based TPCK by calculating (manifest) factor scores using Bartlett's method (Bartlett, 1937).

Mathematics-Specific PCK

To measure PCK, we used an adapted version of the well established instrument provided in Buchholtz et al. (2016). From the available 14 original items, we had to drop one item that required drawing and thus was not transferable from paper to online format. Another item was dropped to assure that each sub-facet (content-related and pedagogical-related perspective on PCK) contained an equal number of items. Therefore, our instrument comprised 12 multiple-choice items in which participants had to apply their PCK from both a content-related and pedagogical-related perspective (e.g., "Consider in the following cases of activities in math class, which of the two forms of performance assessment portfolio or written test – best suits the following activities: Please indicate portfolio or written test for each of the activities: a) Working on problem-solving tasks, b) Working on tasks related to calculus of variations, c) Working on tasks of algebraic manipulations"; see Buchholtz et al., 2016, for details). A one-dimensional CFA demonstrated good fit (RMSEA = 0.033; SRMR = 0.097, CFI = 1.00) to the data. Participants randomly received 8 out of 12 items and scored one point for each item if they selected the correct answer(s). To account for the planned missing values, we specified a Rasch model. For the subsequent analysis, we estimated pre-service teachers' PCK by means of Weighted Likelihood Estimates (WLEs; Warm, 1989).

Technological Knowledge (TK)

To measure TK, we adapted an instrument by Fütterer et al. (2023). The original test comprised 26 single-choice items that required to apply knowledge of operating technologies that are commonly (but not exclusively) used in schools (e.g., spreadsheets or PowerPoint). To keep the test battery as small as possible, we dropped 9 items that we considered to be least relevant for high-quality instruction in the classroom (e.g., one item being dropped asked participants to choose the appropriate way to send an e-mail). Therefore, our instrument contained 17 single-choice items of which participants received 9 randomly chosen ones (e.g., “You want your students to work on a collaborative writing document. You use a common web-based Etherpad (collaborative real-time editor; e.g., edupad.ch, ZUMpad). You want to be able to distinguish the entries of different students. What specific function do Etherpads offer you? Choose the correct response: a) I can activate the function that the author colors are visible., b) I can activate the function that the students’ name abbreviations are displayed before each of their entries., c) I can activate the function that only one student writes on the pad at a time, d) I can activate the function that each student writes on his or her own pad.”). Again, a one-dimensional CFA demonstrated good fit to the data (RMSEA <0.001, SRMR = 0.094, CFI = 1.00). For each item that was answered correctly, participants received one point. Like for PCK, we specified a Rasch model and calculated WLEs to estimate participants’ TK.

9.3.2.2 Other Instruments

Self-Reported TPCK

To measure self-reported TPCK, we used an adapted version of the questionnaire by Schmidt et al. (2009) comprising five items based on rating scales in which participants assessed their knowledge of integrating technologies for teaching mathematics (e.g., “I can teach lessons that appropriately combine mathematics, technologies, and teaching approaches”). The scale ranged from 0 = strongly disagree to 4 = strongly agree (Cronbach’s α = 0.78). For the analysis, we estimated the average score across the five items .

Metacognitive Accuracy

To measure the metacognitive accuracy of participants regarding their test-based TPCK, we followed common metacognitive research and asked them to make prospective judgments of learning (JOL) to estimate how well they would perform on the subsequent TPCK test (Golke et al., 2019; Jacob et al., 2020; Maki & McGuire, 2002). To operationalize metacognitive accuracy, we calculated the *Absolute Accuracy Index* as defined in Schraw (2009) which is the squared difference between the test-based TPCK scores and JOL:

$$\text{Accuracy} = \left(TPCK_{JOL} - TPCK_{test-based}\right)^2.$$

Accordingly, larger values of accuracy corresponded to less accurate estimations, whereas values close to zero indicated excellent accuracy. Given that each participant answered five test-based TPCK items, the sum score of test-based TPCK ranged from 0 to 15 (three points per answer). Therefore, the scores for the accuracy ranged from 0 (perfect accuracy) to $15^2 = 225$ (extremely low accuracy).

Given that the Absolute Accuracy Index does not allow to investigate over- or under-estimation (due to the square), we calculated the Bias Index which is defined as the signed difference between the test-based TPCK scores and JOL:

$$\text{Bias Index} = TPCK_{JOL} - TPCK_{test-based}\,.$$

Accordingly, negative scores on the Bias Index indicated underestimation, positive scores overestimation, and values around zero indicated good accuracy.

Prior Experience with Teaching in Schools

To assess prior teaching experience in schools, we used a single dichotomous item in which the participants indicated whether they had completed their practical school term (1 = *prior school experience*) or not (0 = *no prior school experience*).

9.3.3 Procedure

Prior to the start of the study, we obtained approval from the local ethics committee. The pre-service teachers were invited to take part in the study via email or personal invitations during lectures. Upon following the provided link, the pre-service teachers gave consent to take part in the study. At the beginning of the survey, the participants provided background information and their demographic data. Next, they answered the self-reported TPCK questions. Following this, they judged how many of the upcoming test-based TPCK items they would get correct. After the test-based TPCK questionnaire, the participants answered items that tapped their PCK and TK. There was no time constraint for the participants to work on the tests and questionnaires. On average, the participants took 34.9 (SD = 10.68) minutes to complete the survey. They received 10 euros upon completion of the survey.

9.3.4 Analyses to Investigate the Research Questions

To investigate the empirical relationships between test-based TPCK, PCK, and TK (RQ 1a), we calculated Pearson correlation coefficients for each pair of knowledge components. To investigate the predictive power of PCK and TK on test-based TPCK (RQ 1b), we employed a multiple linear regression model, in which we specified PCK and TK as the predictors for test-based TPCK. For more precise estimates, we controlled for gender. To explore whether the predictive power of PCK and TK differed significantly, we applied a t-test in which we tested the hypothesis that the difference between both regression coefficients was zero (Shrout & Yip-Bannicq, 2017). To investigate the empirical relationship between test-based and self-reported TPCK (RQ 2a), we calculated the Pearson correlation coefficient. To examine possible influencing variables on this relationship (RQ 2b), we specified three multiple linear regression models, each of which included self-reported TPCK as an independent and test-based TPCK as the dependent variable. The three models differed regarding the moderator variable, which was gender in the first, prior experience with teaching in the second, and metacognitive accuracy in the third model.

9.4 Results

9.4.1 Descriptives and Preliminary Analysis

All descriptive statistics of the measures used for investigating the research questions are presented in Table 14. To explore gender effects on test-based and self-reported TPCK, TK, PCK and metacognitive accuracy, we conducted two-tailed *t*-tests. Considering the last two columns of Table 14, we found statistically significant differences between male and female pre-service teachers in our sample: Men tended to self-report their TPCK higher than women, $t(139) = -2.15$, $d = .37$ $p = .033$, Further, men demonstrated significantly higher scores regarding TK than women, $t(139) = -2.68$, $d = .50$, $p = .008$.

Table 14

Descriptive Statistics of all Variables Including Two-Tailed t-Test Statistics to Investigate Gender Differences on these Variables

Variables	Whole Sample ($n = 141$)		Men ($n = 41$)		Women ($n = 100$)			
	M	*SD*	*M*	*SD*	*M*	*SD*	$t(139)$	*p*
test-based TPCK[a]	0.00	0.66	0.15	0.60	-0.06	0.68	-1.73	.080
PCK[b]	-0.03	1.02	-0.03	0.91	-0.03	1.06	0.04	.967
TK[b]	-0.02	1.03	0.33	1.09	-0.17	0.97	-2.68	.008
Self-reported TPCK	3.02	0.74	3.22	0.79	2.93	0.71	-2.15	.033
Accuracy	21.74	30.85	23.25	28.12	21.13	32.02	-0.37	.712
Judgment Bias	3.12	3.48	3.43	3.43	2.99	3.51	-0.68	.501
	Exp.[c]	No exp.[d]	Exp.	No exp.	Exp.	No exp.		
Prior school experience	25	116	8	33	17	83		

Note. [a] Bartlett estimates, [b] WLEs,

[c] Number of participants who completed a practical internship in school, [d] Number of participants who did not complete a practical internship in school.

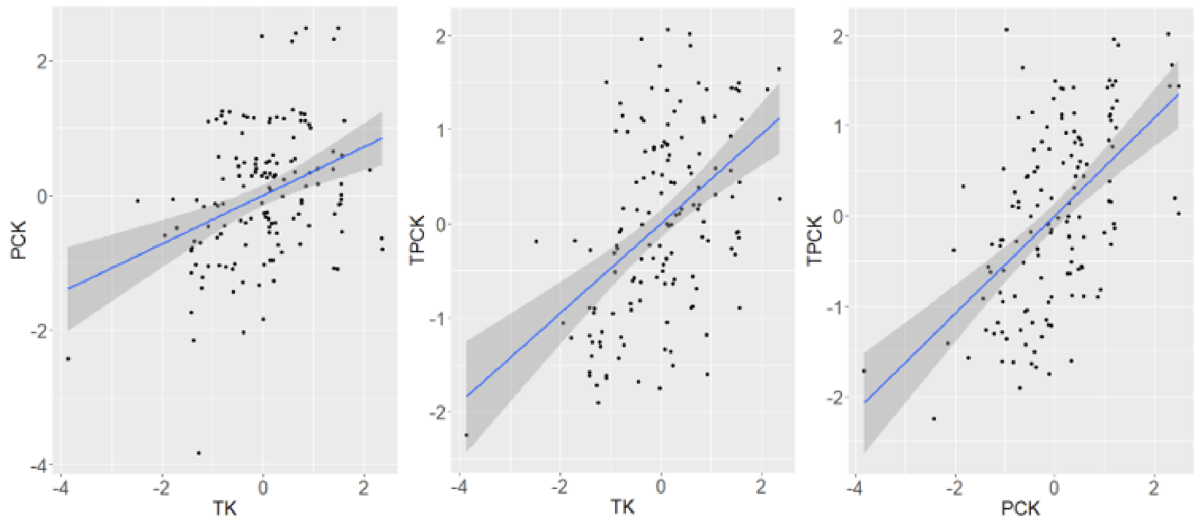
9.4.2 Research Question 1: The Empirical Relationship Between TPCK, PCK and TK

We provide scatterplots for each pair of test-based variables in Figure 9. As suggested by the slopes of the regression lines in the scatter plots (Figure 9), we found a statistically significant positive relationship between PCK and test-based TPCK ($r = .538$, $p < .001$)

indicating that participants who performed well in PCK tended to perform also well in test-based TPCK. Similarly, we found a statistically significant, positive relationship between TK and test-based TPCK ($r = .472$, $p < .001$). Furthermore, we found a statistically significant relationship between TK and PCK ($r = .359$, $p < .001$).

Figure 9

Scatter Plots for Each Pair of Test-Based Measures



Note. In each of the scatter plots, a dot represents the unstandardized score of one participant in the respective measures.

To investigate the predictive power of PCK and TK on test-based TPCK, we specified a linear regression model as detailed in the section 3.4.1. The summary of the statistics can be found in Table 15. Considering the first column of Table 15, we found that the effects of both TK ($\beta = .321$, $p < .001$) and PCK ($\beta = .423$, $p < .001$) on test-based TPCK were (statistically) significantly positive. However, the effect of PCK on test-based TPCK was not significantly larger than the effect of TK on test-based TPCK ($p = .37$).

Table 15

Regression Coefficients of PCK and TK on Test-Based TPCK

Variable	β	*SE*	*t*	*p*
(Intercept)	.000	.007	0.00	1
TK	.321	.007	4.460	< .001
PCK	.423	.007	5.885	< .001
R_{adj}^2				

Note. *N* = 141. *SE* denotes the standard error. B denotes the standardized regression coefficients

9.4.3 Research Question 2: The Relationship Between Test-Based TPCK and Self-Reported TPCK and the Effect of Gender, Prior Experience and Metacognitive Accuracy

The relationship of self-reported TPCK and test-based TPCK was low but statistically significant, $r = .243$, 95% CI [0.081, 0.392], $p = .004$. To investigate possible influencing variables on this relationship, we specified three linear models with either gender, or prior experience, or metacognitive accuracy as moderators. The complete statistics are displayed in Table 16.

Across all three models, we found a statistically significant positive effect of self-reported TPCK on test-based TPCK with varying effect sizes (see Table 16) indicating that pre-service teachers who reported having higher levels of TPCK also performed better in the test-based TPCK questions.

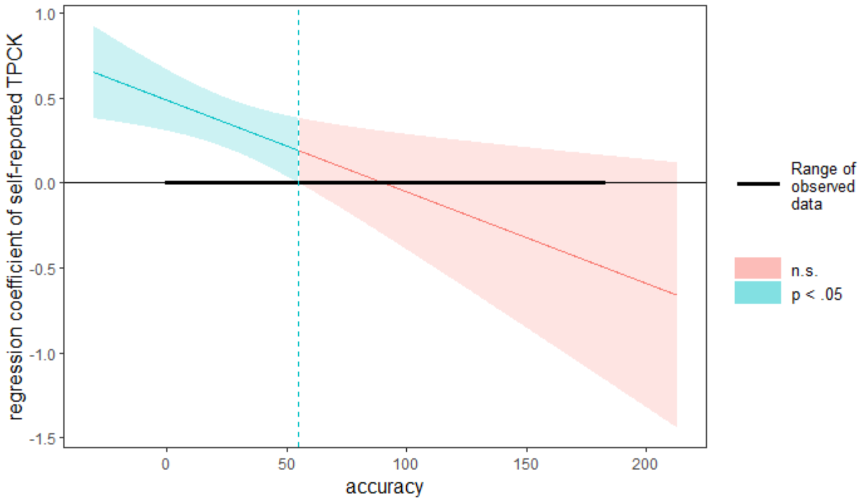
Regarding the main effects of the moderators, we found neither a main effect of gender, (Model 1 in Table 16), nor one of prior experience on test-based TPCK (Model 2 in Table 16). In contrast, the main effect of accuracy on test-based TPCK was statistically significantly, $\beta = -.568$, $p < .001$, indicating that the more accurate pre-service teachers could assess their level of

TPCK (i.e., values of accuracy tended towards zero), the better they performed in the TPCK test.

Regarding interaction effects, we found no evidence that gender or prior experience moderated the relationship between self-reported and test-based TPCK (Table 16). However, we found a statistically significant interaction effect of accuracy, $\beta = -.145$, $p = .010$, which suggests that the relationship between self-reported and test-based TPCK was higher for pre-service teachers who could more accurately assess their level of TPCK. To explore this interaction further, we employed a subsequent Johnson-Neyman procedure (Johnson & Fay, 1950). As suggested by the Johnson-Neyman plot (Figure 10), for pre-service teachers whose accuracy was below a threshold, the relationship between test-based TPCK and self-reported TPCK was statistically significant. Put differently, the more accurate participants could self-assess their knowledge regarding technology integration, the stronger both measures (self-reported TPCK and test-based TPCK) were linked.

Figure 10

Johnson-Neyman Plot for the Moderating Effect of Accuracy on the Relationship Between Test-Based and Self-Reported TPCK



Note. The range of observed values of accuracy was [0, 182.25]. Values are represented in unstandardized beta coefficients. When participants' accuracy was below the cut-off value of 52.84 (blue area), the effect of self-reported TPCK on test-based TPCK was statistically significant.

Table 16

Three Different Linear Models Displaying Regression Coefficients of Self-Reported TPCK on Test-Based TPCK with Gender (Model 1), Prior Experience (Model 2), or Metacognitive Accuracy (Model 3) as Moderators

Variable	Model 1				Model 2				Model 3			
	β	*SE*	*t*	*p*	β	*SE*	*t*	*p*	β	*SE*	*t*	*p*
(Constant)	.071	.098	-.724	.470	-.112	.088	-1.281	.202	.015	.065	.232	.817
SR-TPCK[a]	.205	.102	2.00	.047	.177	.087	2.047	.043	.324	.066	4.921	<.001
Moderator												
Gender	.226	.185	1.218	.226								
Interaction	.066	.178	.374	.709								
Experience[b]					.569	.212	2.680	.008				
Interaction					.317	.227	1.395	.165				
Accuracy									-.568	.065	-8.681	<.001
Interaction									-.146	.056	-2.609	.010
R_{adj}^2	.052				.165				.407			

Note. [a] SR-TPCK = Self-reported TPCK, [b] Experience: 0 = Pre-service teacher did not complete practical internship, 1 = Pre-service teacher completed practical internship

9.5 Discussion

In the present study, we shed light on two desiderate that have prevailed in the TPACK ecosystem for years.

First, we investigated the inherent structure of TPACK by employing test-based and subject-specific instruments, and thereby extended prior research that have mainly focused on the relationship of subject-unspecific TPACK-components such as TPK. In particular, we were interested to scrutinize whether the theoretical distinction between PCK and TPCK is empirically warranted. By also including TK as a predictor for TPCK, we were further able to compare the predictive power of TK on TPCK with the predictive power of PCK on TPCK to conclude whether the data are suggestive of the transformative or integrative view of TPACK.

Second, we explored potential factors contributing to the predominant findings of prior research indicating that test-based and self-report TPCK instruments are only related to a limited extend. To do so, we investigated potential influencing variables that have been shown to be confounded with the level of self-reported TPCK (i.e., gender, experience, and metacognitive accuracy).

9.5.1 Main Findings

9.5.1.1 Research Question 1: The Inherent Structure of TPACK

Concerning the inherent structure of TPACK, the results suggest that TPCK and PCK are moderately related ($r = .538$) and therefore similar, yet different knowledge components (Angeli & Valanides, 2009). In terms of the empirical distinguishability, we can assert that TPCK represents a knowledge facet on its own rather than a sub-facet of PCK, as both constructs only share 30% of common variance. Considering the predictive power of PCK and TK on TPCK, our findings suggest that both PCK and TK moderately predicted the level of pre-service teachers' TPCK. This finding indicates that TK, too, is essential for TPCK which contrasts the findings by von Kotzebue (2022) who did not find a statistically significant effect of TK on TPCK in the context of biology education. This finding highlights the situated character of TPACK in a (domain) specific context and calls for further investigations in different domains.

The similar *closeness* of TK and PCK with TPCK highlights the importance of both constructs for domain-specific teaching with technologies. Moreover, comparing the predictive power of PCK on TPCK ($\beta = .423$) in our sample with predictors for TPCK from the study of von Kotzebue (2022), we further note that PCK seems to be more predictive for TPCK than TCK but less predictive than TPK. Again, one needs to be cautious as TPCK is highly context sensitive (Brianza et al., 2022; Mishra, 2019) and comparisons across different samples are hence limited. Contrasting our findings with prior studies based on self-reports, we note that we could not confirm prior findings that "TPCK is primarily influenced by the hybrid components TPK and PCK" (Schmid et al., 2020a, p. 9) as we found a statistically significant contribution of TK to TPCK, too. Also, our findings are in line with some studies that showed that PCK was predictive of TPCK (e.g., Celik et al., 2014; Schmid et al., 2020a) while contrasting findings from other studies that instead found TCK and TPK to be predictive of TPCK (e.g., Dong et al., 2015; Koh, Chai & Tsai, 2013).

9.5.1.2 Research Question 2: The Relationship Between Test-Based and Self-Reported TPCK

Our results suggested that test-based TPCK was only linkedweakly to self-reported TPCK which is in line with an ever-growing body of evidence from previous research (Drummond & Sweeney, 2017; Max et al., 2022; von Kotzebue, 2022). In contrast to prior studies, however, we also investigated boundary conditions on this relationship by including possible influencing variables, which allowed us to recognize the following patterns in our data.

9.5.1.2.1 The Role of Gender

Male pre-service teachers self-reported their TPCK abilities significantly higher than females (Table 1) which is in line withprior results from studies based on self-reports (see 2.3.1). At the sametime, there was no maineffect of gender on test-based TPCK. Taking both findings together, we may conclude that self-reported TPCK does induce gender-effects that stem from the way TPCK is assessed. At the same time, our moderator analyses did not provide evidence for a moderating gender effect on the relationship between test-based and self-reported TPCK.

9.5.1.2.2 The Role of Prior Experience

We found a main effect of experience on test-based TPCK indicating that pre-service teachers who had had the opportunity to teach students in authentic school settings were able to integrate technology more effectively to support students' learning. This finding highlights the crucial factor of providing pre-service teachers with opportunities to gain experience and reflect on their actions as suggested by the SQD-model (Tondeur et al., 2012) and prior studies (e.g., Lachner et al., 2021). Similar to gender, we did not find a moderating effect of experience on the relationship between self-reported and test-based TPCK.

9.5.1.2.3 The Role of Metacognitive Accuracy

We did not only find a significant main effect on TPCK but also a significantly moderating effect of metacognitive accuracy on TPCK suggesting that the relationship between self-reported and test-based TPCK was higher for those pre-service teachers who assessed their level of TPCK more accurately.

9.5.1.3 Theoretical Implications

Our findings reveal two principal theoretical insights. First, while PCK and TPCK are moderately related, they still seem to be distinct knowledge components mirroring findings about the empirical distinguishability of PCK and CK (Krauss et al., 2008). Therefore, the theoretical distinction between PCK and TPCK seems to be warranted despite existing conceptualizations that consider TPCK a sub-facet of PCK (Schubatzky et al., 2023). At the same time, the results suggest that PCK and TK are both equally necessary for technology-enhanced instruction in subject-specific teaching. Also, PCK and TK could not explain the whole variance of TPCK indicating that TPCK goes beyond the mere integration of PCK and TK. This may be suggestive of TPCK being of transformative nature which is in line with recent findings (von Kotzebue, 2022). Second, our findings revealed that metacognitive skills play a central role in the reliability of self-report instruments. Put differently, self-report measures seem to be a suitable way to assess pre-service teachers' knowledge of technology integration if and only if their level of metacognitive accuracy is high. Against this background, developing self-report instruments including items with more context may be a promising pathway to help teachers judge their knowledge more accurately (see Sailer et al., 2021, for a first attempt in this regard).

9.5.1.3.1 Practical Implications

What are the practical implications of our findings? First, our findings highlight the distinct role of knowledge regarding technology integration in a subject-specific setting. Seemingly, providing high quality teaching with technology is not merely dependent on Pedagogical Content Knowledge. Instead, (pre-service) teachers need to combine their knowledge of good mathematics teaching and learning with their knowledge of technologies. Therefore, pre-service teacher trainings should provide plenty opportunities for preservice teachers to deliberately practice integrating PCK with TK to reach TPCK. Second, the main effect of prior experience on TPCK indicates the need for early practical experiences in pre-service teacher education. The earlier pre-service teachers are allowed to experience authentic teaching and reflect on their acting, the better they seem to be prepared for their future life as teachers. Third, the crucial role of metacognitive accuracy calls forth the need for not only focusing on cognitive but also on metacognitive competencies throughout pre-service teacher curricula. For example, constant formative diagnoses within lectures and seminars, or the application of diaries in which pre-service teachers reflect on their learning may pose adequate strategies to improve pre-service teachers' metacognitive accuracy (Cohen-Sayag & Fischl, 2020; Saks & Leijen, 2019).

9.5.1.3.2 Limitations and Conclusion

One needs to consider several limitations when interpreting our findings. First, our study was of correlational nature. Therefore, causal interpretations should be avoided. For example, it remains unclear whether high levels of PCK or TK automatically translate to high levels of TPCK. Here, more research is needed with strong experimental research designs to establish causality (see Evens et al., 2018, for an experimental approach in the context of English-specific PCK). Second, we implemented the study in an online survey which carries the risk of little control and inattentiveness of participants. At the same time, the use of an online format, not requiring pre-service teachers to provide identifiable data, likely mitigated social desirability biases. Third, we employed a self-selected sampling technique, which may have introduced a volunteer bias, potentially affecting the generalizability of the findings. Fourth, our TK focused narrowly on operational aspects, omitting other crucial facets of TK, such as ethical consequences (Gómez-Trigueros and Yáñez de Aldecoa, 2021) or future technologies like artificial intelligence (Celik, 2023). Fifth, we included only some, but not all, of the seven TPACK-components in our study. Possibly, some of the unexplained variance in TPCK could be accounted for by the varying levels of TCK or PK. Therefore, we encourage future researchers to conduct studies considering all seven TPACK-components. To implement such a study, however, researchers need to invest more resources into the development of parsimonious subject-specific test-based instruments (e.g., multiple choice tests, see Große-Heilmann et al., 2023, for first attempts in the field of physics education) to make sure not to overburden participants and to keep studies economically feasible. Lastly, our study only allows to draw conclusions regarding the inherent structure of TPACK from mathematics pre-service teachers trained at universities in Germany. Given the context sensitivity of TPACK (Mishra, 2019), it is questionable to what extent our results translate to different subjects or levels of expertise, such as in-service teachers. Therefore, future research is necessary to investigate whether our results pertain across different contexts.

Despite these limitations, our findings contribute to the nuanced understanding of the inherent structure of TPACK in a subject specific context, and provide valuable insights into the peculiarities of different assessments.

10 *Study 3*: Fostering Pre-Service Teachers' TPACK: A Quasi-Experimental Study

The content of this chapter has been published in Computers & Education. Minor differences may exist between this chapter and the final published version.

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Abstract

Against the backdrop of preparing students for a digitalized future, supporting pre-service teachers' development of technological pedagogical content knowledge (TPACK) has become paramount in pre-service teacher education. Whether and how pre-service teachers' acquisition of TPACK could be supported is still an open question, as previous research predominantly relied on correlational data and/or self-report assessments. Based on previous research, we developed subject-specific versions of a TPACK-module to support the acquisition of TPACK. Further purpose of the TPACK-module was to enhance technology-related motivation, as motivational orientations have been documented to be crucial for technology integration. We evaluated the effectiveness of the module by means of a quasi-experimental field study. Pre-service teachers (*N* = 208), enrolled in five subjects, attended regular semester courses on subject-matter pedagogies. In half of the courses, we randomly implemented subject-specific TPACK-modules (duration: three weeks), in which pre-service teachers were taught in using technology for subject-matter teaching, whereas the control condition attended the regular courses without the TPACK-module. We found that pre-service teachers in the courses with the TPACK-modules acquired more TPACK than those in the control courses without the TPACK-modules. Significant effects were also obtained for preservice teachers' technology-related self-efficacy and their perceived support for technology integration. The effectiveness of the TPACK-modules could be explained by the obtained support for technology integration. The findings highlight the central need of adequate support for preservice teachers' development of technology-related professional knowledge and motivation in teacher education programs.

Keywords: Professional knowledge, Technology integration, TPACK, Teacher education

10.1 Introduction

Against the background of digitalization, integrating technology into teaching is paramount for teachers to prepare students for a digitalized future. As a consequence, teachers are required to integrate technology into their teaching to support students' learning (Siddiq et al., 2016). Despite the potential of integrating technology for teaching, however, research has demonstrated that in many educational systems teachers rarely adopt technology into teaching (Fraillon et al., 2020).

Therefore, it is generally argued that pre-service teachers should acquire subject-specific professional knowledge regarding technology integration to be able to support their future students' learning. The professional knowledge related to a successful subject-specific integration of technology is commonly subsumed under the concept of *technological pedagogical content knowledge* (cf. TPACK, Mishra & Koehler, 2007). Likewise, pre-service teachers should develop adequate motivational orientations (e.g., self-efficacy, utility to adopt educational technology, teaching enthusiasm, see Backfisch et al., 2020; Kunter, Klusmann et al., 2013), as motivation is essential for persistence and performance. To date, only few empirical examples of interventions exist which tackle pre-service teachers' acquisition of TPACK and technology-related motivation by means of (quasi-)experimental research, which allow to draw conclusions regarding the effectiveness of such interventions (for scarce exceptions see Alayyar et al., 2012; Kramarski & Michalsky, 2010; Rienties et al., 2020). However, a large proportion of these quasi-experimental interventions often focused on professional knowledge for technology integration in a domain-general manner (i.e. TPK), and often ignored the subject-specific knowledge component of technology integration (i.e., TPACK), as identified by several systematic reviews (Tseng et al., 2020; Voogt et al., 2013). TPACK, however, is often regarded as essential to integrate technology into subject-specific teaching in a meaningful manner (Mishra & Koehler, 2007). Against the background of lacking available quasi-experimental evidence on subject-specific TPACK-interventions, we conducted a quasi-experimental study in which we compared effects of a TPACK-intervention to a control intervention, which did not contain the TPACK-intervention. The TPACK intervention followed general principles of teacher education (e.g., approximation of practice, see Grossman et al., 2009) and specific evidence-based guidelines for pre-service teacher education regarding technology integration (Synthesis of Qualitative Data (SQD) *model*, see Tondeur et al., 2018; Tondeur et al., 2012). Moreover, the intervention was adapted to five subjects and, therefore, comprised domain-specific aspects of technology-integration into subject-specific teaching.

10.1.1 Pre-Service Teachers' Professional Knowledge to Integrate Educational Technology

TPACK is a ubiquitous conceptual framework to describe teachers' professional knowledge regarding technology integration (Mishra & Koehler, 2007). TPACK is based on general conceptualizations by Shulman (1986) who proposed three knowledge components for professional teaching (see also Baumert et al., 2010; Hill et al., 2008; Kunter, Klusmann et al., 2013): a) *Content knowledge* (CK) is regarded as teachers' subject-specific knowledge related to the content to be taught; b) *pedagogical knowledge* (PK) is operationalized as generic instructional knowledge to design effective learning environments (Voss et al., 2011) and refers to domain-general instructional strategies that should support students' learning (Baumert et al., 2010; Voss et al., 2011); and c) *pedagogical content knowledge* (PCK) is the knowledge about content-specific teaching strategies and students' (mis-)conceptions, which helps teachers adapt content knowledge to students' potential prerequisites and provide adequate representations (Baumert et al., 2010; Hill et al., 2008; Shulman, 1986).

In their TPACK framework, Mishra and Koehler (2007) added another knowledge component, technological knowledge (TK), which refers to teachers' professional knowledge regarding technologies, such as digital tools and infrastructure. Due to the addition of technological knowledge, three additional "t-intersections" have emerged (Scherer et al., 2017), which are commonly associated with teachers' technology integration: *Technological content knowledge* (TCK) comprises knowledge about how to use technology in different content-specific areas; *technological pedagogical knowledge* (TPK) refers to teachers' generic knowledge of technology integration to support students' learning and is not bound to specific contents (Koehler & Mishra, 2009; Scherer et al., 2017); and *technological pedagogical content knowledge* (TPACK) specifically refers to content-specific teaching strategies in the context of technology integration (Koehler & Mishra, 2009). For successful technology integration, Koehler and Mishra (2009) have emphasized the central role of TPK and TPACK. Whereas TPK should help teachers apply their knowledge about teaching with technology in a generic manner, TPACK should particularly enable teachers to integrate educational technology for content-specific teaching strategies (Koehler & Mishra, 2009).

However, to date only limited empirical evidence is available on the cognitive structure of TPACK, as previous studies predominantly relied on assessing professional knowledge by means of self-reports instead of using test-based instruments (e.g., Archambault & Barnett, 2010; Lin et al., 2013; Scherer et al., 2017; see Akyuz, 2018 for exceptions). Contrarily, self-reported knowledge may rather reflect teachers' confidence to integrate technology, and thus may constitute proxies of teachers' technology-related self-efficacy beliefs instead of objective measures of professional knowledge (Backfisch et al., 2020; Brantley-Dias & Ertmer, 2013; Cheng & Xie, 2018; Lachner et al., 2019; Scherer et al., 2017; Willermark, 2018). Furthermore, although self-assessments have been shown to correlate with direct measures of TPACK to a limited extent, they may largely depend on the participant's skills to accurately assess his or her own knowledge (see Prinz et al., 2020, for a general overview between self-assessments and test-based assessments). The development of test-based assessments for TPACK, however, is just at the beginning (see Drummond & Sweeney, 2017, for a scarce example of measuring TPACK using a test-based instrument) given that most previous studies have relied on self-reported knowledge (Koehler et al., 2012; Willermark, 2018).

10.1.2 Technology-Related Motivation

Besides the acquisition of TPACK, enhancing technology-related motivation is discussed to be critical for successful technology-integration, as adopting technologies requires teachers to deliberately change their teaching practices (see Backfisch, Lachner et al., 2021; Hussain et al., 2018). The research landscape of technology-related motivation is rooted in different conceptual frameworks, such as technology-acceptance models (TAM, see Scherer et al., 2019; Teo, 2011) or expectancy-value models (Backfisch et al., 2020; Eccles & Wigfield, 2002), which highlight the role of self-efficacy and perceived utility (cf. usefulness, see Backfisch, Scherer et al., 2021, for an empirical comparison). For instance, Scherer et al. (2019) synthesized the findings from 114 survey studies which used TAM as a theoretical framework and examined the correlation between teacher motivation (i.e., perceived utility, technology-related self-efficacy) and their intention to use technologies and the self-reported frequency of using technologies for teaching. The authors found that self-efficacy and perceived utility predicted teachers' intention to use technology and the frequency of technology-integration.

Relatedly, Backfisch et al. (2020) more closely investigated the quality of technology-integration, by applying a lesson-plan scenario. The authors required mathematics teachers (N = 94) differing in their teaching expertise (i.e., pre-service teachers, trainee teachers, and in-service teachers) to answer a test measuring their professional knowledge regarding the basic components of TPACK (i.e., CK, PCK, TK), and report their motivation to integrate technology (i.e., self-efficacy, utility value). Furthermore, the teachers generated a lesson plan to teach the Pythagorean theorem with educational technology. The authors found that teachers having higher levels of expertise (i.e., trainee teachers, in-service teachers) provided lesson plans in which technology was used to better enhance teaching quality, than the ones by novice teachers (i.e., pre-service teachers, $\eta_p^2 = .16$). The quality of the lesson plans was mainly associated with teachers' perceived utility (see also Backfisch, Lachner et al., 2021, for a longitudinal replication), suggesting that teacher motivation played a distinct role in technology integration.

10.1.3 Approaches to Support Pre-Service Teachers' Development of TPACK and Technology-Related Motivation

he previous findings highlight the central role of TPACK as well as technology-related motivation for technology integration and suggest that particularly pre-service teachers may require assistance during the course of teacher education. Research on teacher education has provided several design principles on how interventions should be designed to foster pre-service teachers' development of TPACK (Hofer & Grandgenett, 2012). Based on general intervention models of teacher education (e.g., Grossman et al., 2009; Korthagen et al., 2006), in their systematic review, Tondeur et al. (2012) developed a conceptual framework called the SQD (Synthesis of Qualitative Evidence) model which proposes six key features to foster pre-service teachers' acquisition of TPACK. From a motivational perspective, these features are regarded as enhancing pre-service teacher motivation (Howard et al., 2021), such as their self-efficacy or their enthusiasm to teach with technology (i.e., technology-related teaching enthusiasm, see also Kunter, Klusmann et al., 2013; Lauermann & König, 2016, for related discussions on general teaching enthusiasm).

In initial phases of skill acquisition, the use of *role models* (feature 1) should help pre-service teachers acquire initial TPACK by observing good-practice examples in which effective strategies of technology integration are modeled (Howard et al., 2021; Wekerle & Kollar, 2021). The use of such models should further reduce the initial demands of technology integration, as pre-service teachers can observe prototypical practices of technology integration and help them develop transferable and flexible knowledge structures (Wekerle & Kollar, 2021).

Furthermore, Tondeur et al. (2012) highlighted the role of guided practice, in which pre-service teachers learn how to use educational technology for their teaching. Ideally, such practices should be followed by the principle of approximation of practice (i.e., increasing practice experiences combined with decreasing instructional support, see Grossman et al., 2009) to provide pre-service teachers with learning opportunities that are proximal to their current level of professional development. Therefore, the enactment of *design-based practices* is highlighted (feature 2: instructional design), such as lesson planning (e.g., Backfisch et al., 2020; Kramarski & Michalsky, 2010), which should be continuously supplemented with more practice-oriented *authentic experiences* (feature 3). For instance, micro teachings (Grossman et al., 2009) can help pre-service teachers practice parts of the teaching process in a live role-play, which allows them to capture and continuously repeat distinct teaching sequences in a decomposed setting. *Collaboration* is regarded as another key feature in the development of TPACK (feature 4), as pre-service teachers can discuss successful or less successful ways of integrating technology and build up a community of practice (Howard et al., 2021; Little, 2002).

Throughout these learning opportunities, pre-service teachers are required to critically *reflect* upon the role of educational technologies and their professional development (feature 5) to further engage in a process of continuous learning. The final key feature (feature 6) involves the use of formative *feedback* on students' design-based practices (Kleinknecht & Gröschner, 2016), which is regarded to be effective in supporting pre-service teachers' TPACK.

Research on evaluating the design features of the SQD-model has gained considerable interest in the last decade. For instance, Tondeur et al. (2018) followed a survey design to examine relationships between the subjective availability of the SQD-features and professional skill development and found medium to large relations between pre-service teachers' perceptions of the availability of the SQD-key features and their self-reported TPACK (see Baran et al., 2019; Howard et al., 2021, for similar findings). In a follow-up mixed method study, Tondeur et al. (2020) replicated the quantitative findings and conducted qualitative interviews with a select group of pre-service teachers. These interviews revealed that the availability of role models was subjectively important for students' skill development. However, it has to be noted that correlational surveys do not allow to draw conclusions about the role of the availability of such design features on pre-service teachers' TPACK, as correlation commonly does not imply causation. Against this background, Hsu and Lin (2020) implemented a four-week training module based on the SQD-features and measured self-reported TPACK-gains from pre- to posttest. Overall, they found gains of TPACK, as a first hint of the effectiveness of the intervention. Moreover, these gains were related to the perceived availability of the SQD-features (i.e., reflection). However, the absence of a control group and test-based measurements in this study makes it difficult to gauge whether these gains resulted due to the intervention or due to alternative explanations such as mere maturation. An exception regarding the experimental investigation of technology-related interventions with test-based instruments is the study by Kramarski and Michalsky (2010). Kramarski and Michalsky randomly assigned pre-service teachers to two versions of a semester course. The main aim of the courses was to foster domain-general technological pedagogical knowledge (TPK, see Lachner et al., 2019) in the specific context of hypermedia environments. In both courses, pre-service teachers received instruction on how to implement hypermedia environments to foster students' learning processes and were engaged in collaborative design tasks to deepen their previously acquired TPK. However, in the intervention course, pre-service teachers received additional metacognitive support to critically reflect upon the learning content. The authors demonstrated that the pre-service teachers in the intervention course outperformed the pre-service teachers in the control course in their acquisition of TPK. The amount of reflection was substantially correlated with the acquisition of TPK. The findings by Kramarski and Michalsky (2010) provide important evidence on the role of reflection phases for the development of TPK. However, it must be noted that the experimental study only comprised the acquisition of TPK (in the context of hypermedia instruction) and only one specific type of support feature, namely reflection.

10.1.4 The Present Study: Fostering Pre-Service Teachers' Acquisition of TPACK and Motivation

The primary goal of the present article was to investigate whether short three-week TPACK-modules, implemented and adapted in regular subject-specific university pre-service teacher education courses, can enhance pre-service teachers' acquisition of TPACK and technology-related motivation. The TPACK-modules were based on the SQD-model and general principles of teacher education (Grossman et al., 2009). Following a quasi-experimental approach, the TPACK-modules were compared to control courses which did not include the TPACK-modules. We collected pre-service teachers' technology-related professional knowledge by means of objective knowledge tests. In addition to test-based TPACK-assessments, we also assessed TPK (Lachner et al., 2019), as well as motivational variables (perceived utility, self-efficacy, teaching enthusiasm) to portray a broad picture of pre-service teachers' skill development. Furthermore, we additionally collected assessments of perceived support regarding technology integration (Tondeur et al., 2018) as a potential explanatory variable for why the TPACK-modules were effective (see also Hsu & Lin, 2020). We tested the following hypotheses which were pre-registered on https://aspredicted.org/:

1) Pre-service teachers in the TPACK-intervention outperform pre-service teachers in the control condition in the knowledge tests (TPK, TPACK).
2) Pre-service teachers in the TPACK-intervention show higher levels of technology-related motivation (self-efficacy, utility-value, teaching enthusiasm) than pre-service teachers in the control condition.
3) Pre-service teachers in the TPACK-intervention report higher levels of subjective support than pre-service teachers in the control courses.

Additionally, as an exploratory analysis, we examined whether the effectiveness of the TPACK-module could be explained by the perceived subjective support during the intervention by means of multilevel mediation analysis.

10.2 Method

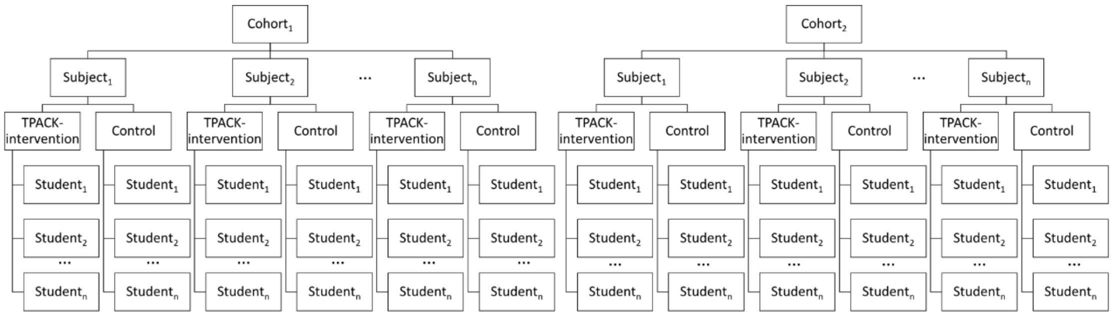
10.2.1 Study Site and Participants

The quasi-experimental study was implemented in the pre-service teacher education program of a southwestern German university (27,000 students, 4,000 pre-service teachers) with a special emphasis on secondary education. In the teacher education program (consecutive Bachelor/Master program), pre-service teachers choose two subjects (in total 25 subjects) and attend content-specific courses (CK, PCK), as well as pedagogy courses (PK). The study was embedded in the Bachelor program with a strong focus on content knowledge and pedagogical content knowledge. For the study, five subject-matter pedagogy experts agreed to participate in the study (biology, mathematics, teaching English as a foreign language, German, philosophy). For each subject, we aimed to recruit two parallel courses (same topic and teacher) per semester term, ideally resulting in 20 courses (5 subjects by 2 cohorts by 2 courses); one of the courses served as the experimental condition and the other as a control condition (see Figure 11 for an overview).

To ensure test power, we computed an a-priori power simulation study. This simulation study would allow to empirically investigate whether the intended sample size and number of courses would be sufficient to detect an effect of our intervention. We could not base our effect size estimates on prior research, as the previous studies were either correlational, based on self-report data, or constituted generic TPK-interventions. Therefore, we followed the rule of thumb definition by Hattie (1992) and opted for detecting medium effect sizes at least ($d = 0.50$). We tested for a multilevel-model (see Figure 11), in which pre-service teachers ($n = 12$) were nested within subjects ($k = 5$) and cohorts ($j = 2$) and ran 1,000 simulations. Based on an alpha-level of $\alpha = .05$, we would achieve excellent test power of $1\text{-}\beta = 93$ % to find an effect of the experimental condition with the estimated number of courses and students. However, the actual sample size of pre-service teachers was $N = 208$ which fell below the intended level. We were not able to recruit a control course in biology due to restricted availability of courses during the COVID-19-pandemic. Therefore, we re-ran a power simulation, a-priori to the data analysis. To account for potential differences among cohorts due to the pandemic, we decided to control for the cohort as a further randomized factor in the model. Power was still excellent, $1-\beta = 91$ % and above the conventional level of 80 %.

Figure 11

Design of the Current Study



Note. The design of the study had a nested data structure, as students were nested within the TPACK-intervention versus the control condition within five different subjects (EFL, biology, math, philosophy, and German) across two student cohorts (winter-term, summer-term).

The recruited pre-service teachers were on average 22.67 ($SD = 2.55$) years old and in the end of their bachelor program, in their 6th semester ($SD = 2.44$). The number of participating pre-service teachers slightly varied across the five subjects ($29 < n < 53$).

10.2.2 Design

The study was realized as a quasi-experimental field study in which courses were randomly assigned to experimental conditions: Regular course + TPACK-module ($N = 88$ pre-service teachers) versus a regular-course only, as a business-as-usual control condition ($N = 120$ pre-service teachers). As we had a nested data structure (pre-service teachers nested within subjects nested within cohorts), we applied a three-level random coefficient model to take the multi-level structure into account. As dependent variables, we used pre-service teachers' technology-related motivation (i.e., self-efficacy, perceived utility, enthusiasm to teach with technology) and pre-service teachers' test performance (TPK, TPACK). Further dependent variables encompassed the perceived subjective support for technology integration during our intervention. We controlled for cohort and subject by modeling random factors.

10.2.2.1 Design of the TPACK-Module

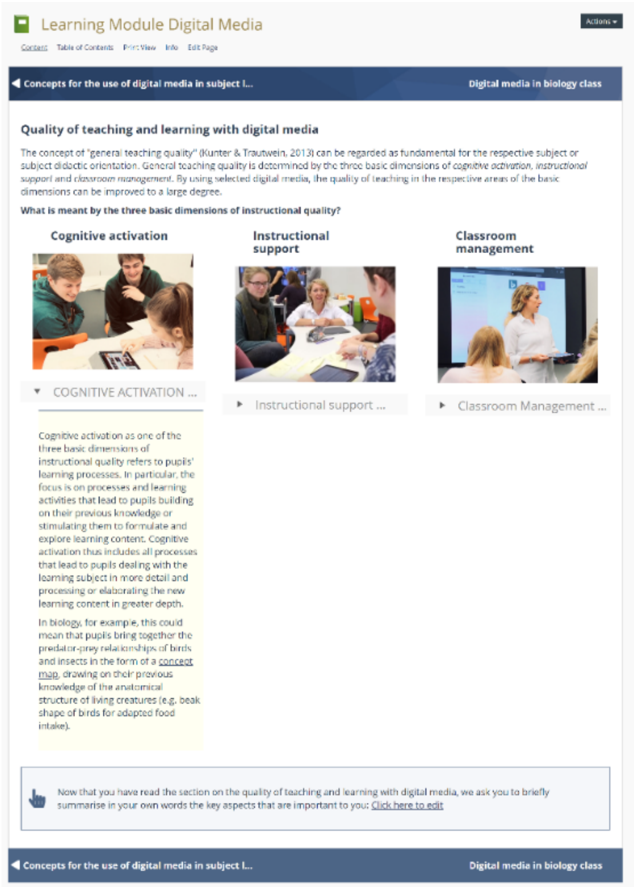
The TPACK-module was based on the SQD-model (Tondeur et al., 2012), as well as general principles of teacher education (Grossman et al., 2009) and was implemented in regular courses in five subject-matter pedagogies (biology, mathematics, teaching English as a foreign language, German, philosophy). The module was held by trained certified subject-matter experts, which also developed the TPACK-modules. The module lasted three weeks. The structure (but not the subject-specific content) of the module was identical across subjects. The materials of the TPACK-modules were implemented as Open Educational Resources and can be seen under the anonymized link.

Overall, the TPACK-module considered *reflection, collaboration* and *feedback* as recurring design features of the SQD-model during the entire module. The three single sessions emphasized different SQD-features (i.e., role models, design practices, authentic experiences) with increasing approximation of practice.

In session 1, the pre-service teachers were introduced to subject-specific principles of technology integration via an online learning module (see Figure 12).

Figure 12

Translated Example Page of the Online Module as Preparation for the First Face-to-Face Session



In that module, they received direct instruction on how technology can be integrated to improve teaching quality. For each subject, we focused on subject-specific methods of technology integration and provided the pre-service teachers with two content-specific videos which modelled good-practice examples of technology integration in the particular discipline (e.g., the use of virtual experiments to foster students' scientific reasoning in biology, see Figure 13 for further examples). In those videos, two experts provided conceptual information on the distinct potential of the portrayed technologies from the perspectives of subject-matter pedagogies and educational technology. To increase student reflection, we asked the students to self-explain the instructed concepts. Overall, session 1 aimed at providing *role models* for students (Tondeur et al., 2012).

In session 2, pre-service teachers enacted a collaborative *design task* in small groups. In this design task, they developed a subject-specific lesson plan in which they adopted educational technology (see also Harris et al., 2010). To enhance pre-service teachers' reflection during lesson planning, we used the scheme by Backfisch et al. (2020) which contained a specific set of prompts. To further support pre-service teachers' planning and reflection activities, they received *formative feedback* from the course instructors. Subsequently, the pre-service teachers revised their lesson plans accordingly. Session 2, therefore, mainly emphasized the role of *design-based practices* (Tondeur et al., 2012).

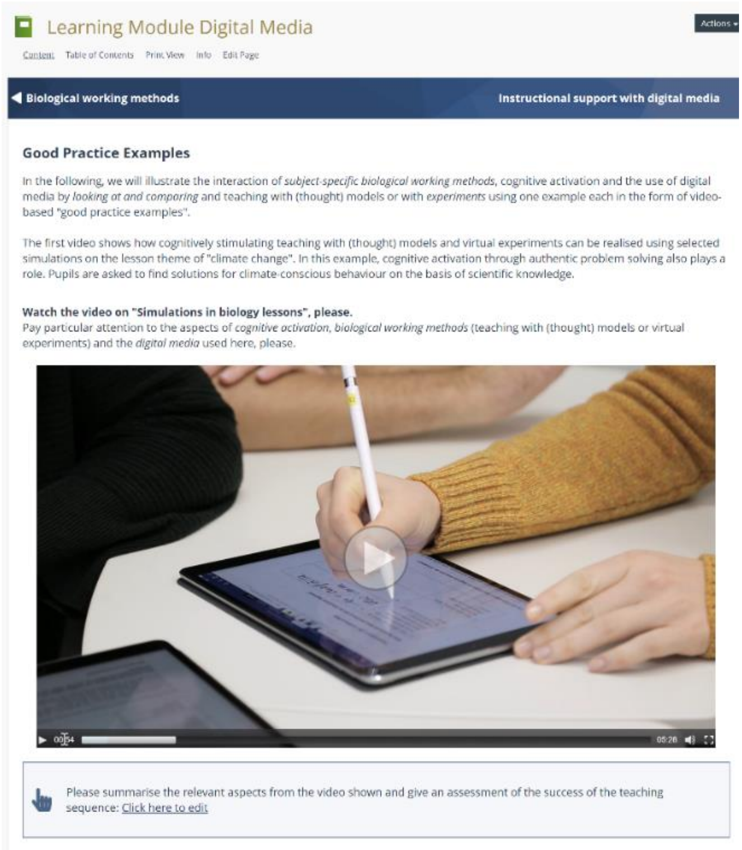
In session three, the resulting teaching sequences were held collaboratively in micro teachings. As such, the pre-service teachers were engaged in *authentic teaching experiences*. Furthermore, the micro teachings were video-taped. As a final homework assignment, pre-service teachers provided peer-feedback on one randomly chosen micro teaching session to further engage their reflection. For that purpose, the pre-service teachers had at hand an annotation tool within the online learning environment which allowed to provide specific comments and feedback on distinct sequences of the assigned micro teaching (see Figure 14 for an example). To scaffold the peer-feedback process, the pre-service teachers additionally had at hand a set of prompts. These prompts were validated in a previous pilot study. For cohort 2, the procedure was identical except for the fact that the micro teachings were held online due to the COVID-19 pandemic. Across the two cohorts, all the pre-service teachers were engaged in the same learning and teaching activities.

In contrast to the students in the TPACK-modules, students in the control conditions received further instruction from the subject-pedagogy experts (i.e., PCK). The control instructors confirmed that they had realized the courses as they usually would. As indicated by post-hoc analyses of the study curricula and reports by the corresponding instructors, teaching

TPACK was not the explicit goal of the courses, although, it could naturally occur during regular teaching. However, as expected, explicitly teaching TPACK occurred very rarely. Only one subject explicitly dealt with a subject-specific technology (i.e., GeoGebra). The main focus of this presentation was on the technical functions but not on pedagogical functions of GeoGebra. Additionally, the duration of the presentations was very short (< 10 minutes) and therefore negligible. As such, we can conclude that TPACK was rarely taught in the control courses. At the same time, the control courses were also comprised of a high degree of student-centered teaching methods particularly in the last third of the courses (e.g., collaborative design-based practices, reflection) in which the TPACK-modules were implemented in the experimental condition. For instance, students also accomplished lesson planning activities or designed learning materials, however, without the explicit intention to integrate technology. In summary, we implemented our intervention in subject-pedagogy courses and compared them to a business-as-usual-condition across five subjects, which helps to test whether the TPACK-module was more effective than current educational practice to prepare students for their future technology integration.

Figure 13

Translated Good-Practice Example in the Online Module

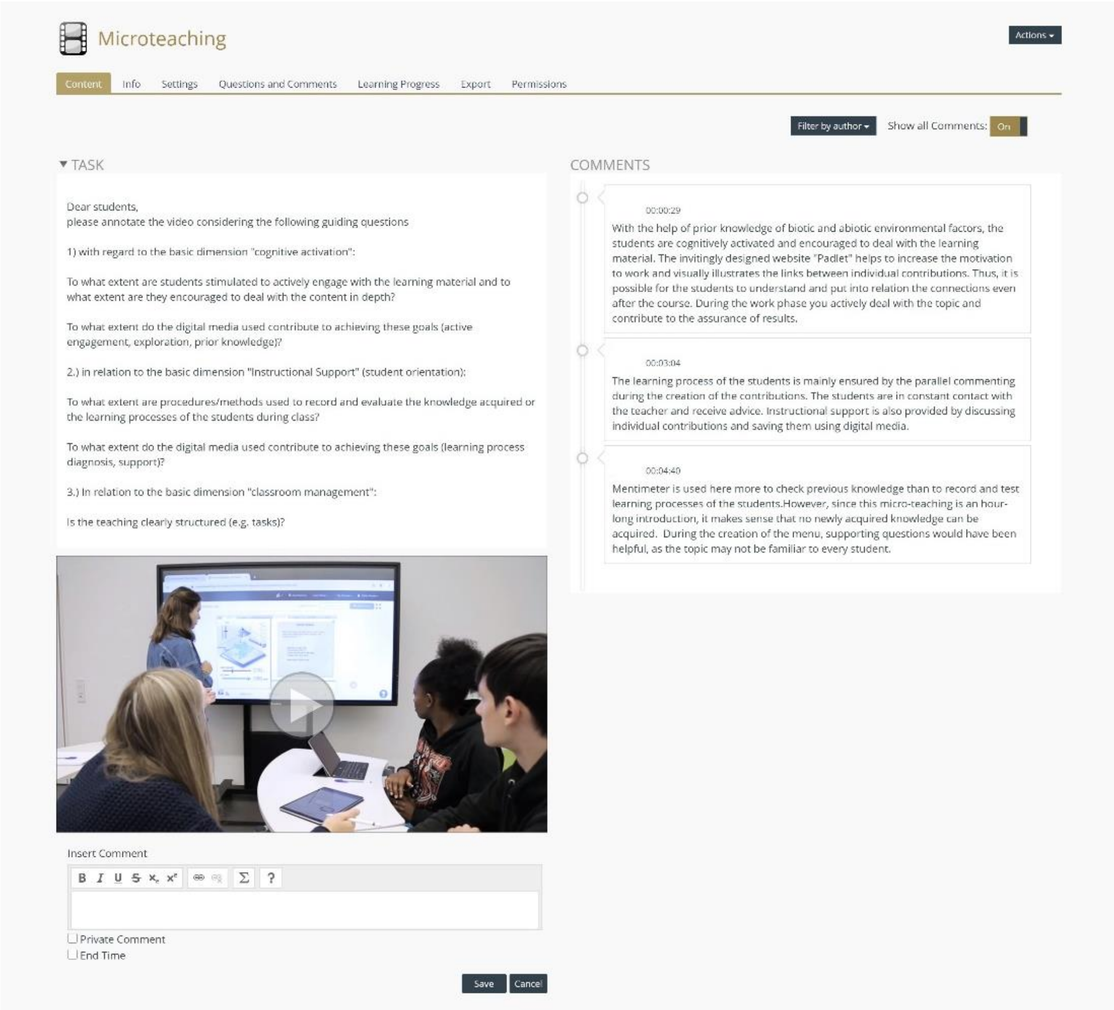


In session 2, pre-service teachers enacted a collaborative *design task* in small groups. In this design task, they developed a subject-specific lesson plan in which they adopted educational technology (see also Harris, Grandgenett, & Hofer, 2010). To enhance students' reflection during lesson planning, we used the scheme by Backfisch et al. (2020) which contained a specific set of prompts. To further support pre-service teachers' planning and reflection activities, they received *formative feedback* from the course instructors. Subsequently, the pre-service teachers revised their lesson plans accordingly. On the basis of the lesson plans, for session 3, the pre-service teachers worked out the instructional design of a distinct teaching sequence of their generated lesson plans. Session 2, therefore, mainly emphasized the role of *design-based practices* (Tondeur et al., 2012).

In session three, the resulting teaching sequences were held collaboratively in micro teachings. As such, the pre-service teachers were engaged in *authentic teaching experiences*. The micro teachings were video-taped. As a final homework assignment, pre-service teachers provided peer-feedback on one randomly chosen micro teaching to further engage their reflection. For that purpose, the pre-service teachers had an annotation tool within the online learning environment at hand which allowed to provide specific comments and feedback to distinct sequences of the assigned micro teaching (see Figure 14 for an example). To scaffold the peer-feedback process, the pre-service teachers had a set of prompts at hand. These prompts were validated in a previous pilot study. For cohort 2, the procedure was identical except for the fact that the micro teachings were held online due to the Covid-19 pandemic. Across the two cohorts, all the pre-service teachers were engaged in the same learning and teaching activities.

Figure 14

Translated Screenshot of the Peer-Feedback Environment



In contrast to the students in the TPACK-modules, students in the control conditions received further instruction in the subject-pedagogies (i.e., PCK). The control instructors confirmed that they had realized the courses, as they usually would do. As indicated by post-hoc analyses of the study curricula and reports by the corresponding instructors, teaching TPACK was not the explicit goal of the courses, however, could naturally occur during regular teaching. As expected, explicitly teaching TPACK occurred very rarely. Only one subject explicitly dealt with a subject-specific technology (i.e., GeoGebra). The main focus of this presentation was on the technical functions but not on pedagogical functions of GeoGebra. Additionally, the duration of the presentations was very short (< 10 minutes) and therefore negligible. As such, we can conclude that TPACK was barely taught in the control courses. At the same time, the control courses also comprised a high degree of student-centered teaching methods particularly in the last third of the courses (e.g., collaborative design-based practices, reflection), in which the TPACK-modules were implemented in the experimental conditions. For instance, students also accomplished lesson planning activities or designed learning materials, however, without the explicit intention to integrate technology. In summary, we implemented our intervention in subject-pedagogy courses, and compared them to a business-as-usual-condition across five different subjects, which helps to test whether the TPACK-module was more effective than current educational practice to prepare students for their future technology integration.

10.2.3 Measures

10.2.3.1 Motivational Pre- and Post-Assessments

We measured technology-related self-efficacy, perceived utility value and enthusiasm to teach with technology at pre- and posttest.

Technology-related self-efficacy. To assess teachers' technology-related self-efficacy beliefs, we used an adapted questionnaire by Schmidt et al. (2009) comprising 5 items which were translated into German by Backfisch et al. (2020). Pre-service teachers had to estimate, whether they would be able to adopt various educational technologies to advance students' learning in their specific subject (e.g., "I can use educational technology to increase the learning success of students"; "I can use educational technology to optimize the methods in my lesson."; pre: Cronbach's $\alpha = .72$; post: Cronbach's $\alpha = .66$). We used a four-point Likert scale ranging from 1 (strongly disagree) to 4 (strongly agree).

Technology-related utility-value. To measure pre-service teachers' perceived utility-value regarding educational technologies, we used the scale by Backfisch et al. (2020, originally developed by van Braak et al., 2004) comprising four items (e.g., "I believe that a progressive introduction of technology into education responds to our society's changing needs"; "I highly value the introduction of technology in the classroom.", pre: Cronbach's α = .76; post: Cronbach's α = .76). The items were answered on a four-point Likert scale ranging from 1 (strongly disagree) to 4 (strongly agree).

Technology-related teaching enthusiasm

We assessed pre-service teachers' prospective teaching enthusiasm with technology, as teaching enthusiasm has been demonstrated to be a strong predictor for teaching quality (see Kunter, Klusmann et al., 2013). Therefore, we used the scale by Bleschke et al. (2001), comprising 5 items (e.g., "I will use educational technology in my future teaching"; "In my future teaching, I will search for possibilities to effectively integrate technology", pre: Cronbach's α = .79; post: Cronbach's α = .78). Again, the questions were answered on a four-point Likert scale ranging from 1 (strongly disagree) to 4 (strongly agree).

10.2.3.2 Knowledge Assessments

Technology-related prior knowledge. We measured pre-service teachers' prior knowledge about concepts and principles related to the domain of educational technology. Therefore, we administered the conceptual TPK-scale by Lachner et al., (2019) comprising different potentials of educational technology (8 items). We particularly decided to assess TPK as prior knowledge assessment as the availability of TPK is often considered as crucial prerequisite for acquiring TPACK (Lachner et al., 2019; Mishra & Koehler, 2007). Furthermore, we wanted to avoid redundancies between pre- and posttest assessments, as –in case of administering the identical questionnaire– part of the intervention effects could have been attributed to re-testing (see Rowland, 2014, for general meta-analytic findings of the testing effect). For each correct solution per item stem, the participants received one point resulting in a maximum score of 32 points (Cronbach's α = .64).

TPK-posttest. To measure pre-service teachers' acquisition of generic technological pedagogical knowledge, we used the situational TPK-test by Lachner et al. (2019). The TPK-posttest contained text-based vignettes which required the pre-service teachers to judge the general appropriateness of educational technology across subjects (e.g., "students create a wiki") for distinct teaching situations (e.g., "for prior knowledge activation"). Consequently, the pre-service teachers had to apply their technological knowledge (e.g., knowledge about the functions of wikis) to distinct teaching situations (e.g., activating prior knowledge). The TPK-posttest comprised 12 items (Cronbach's $\alpha = .69$); 1 point could be achieved per correct answer, resulting in a maximum score of 96 points.

TPACK-posttest. To measure pre-service teachers' subject-specific knowledge about technology integration (TPACK), we developed subject-specific TPACK-tests, which were based on classical test theory (see anonymized link for the entire test documentation). To heighten the construct validity of our instruments, the TPACK tests were constructed by an interdisciplinary research team consisting of experts in the participating subject-pedagogies, educational technology, and methodology. To receive a comprehensive set of items, which represented a broad spectrum of the particular subject, we selected representative problems on the basis of the current federal curriculum for secondary education of the particular subject. Additionally, during the design of the test items, we followed a comparative approach and continuously inspected the comparability of the test versions across subjects. Based on Krauss et al. (2008), in each item, the pre-service teachers were provided with a short text-based vignette in which a subject-specific teaching problem was stated (e.g., mathematics: "Correctly multiplying fractions causes little difficulty for most students. At the same time, however, they find it difficult to understand that multiplying two rational numbers can result in a smaller number in terms of absolute value. How could you use educational technologies as a teacher to prevent these misconceptions? Give reasons for your answer, please."; EFL: "The students in class 7a have troubles understanding when to use the simple past and when to use the present perfect. How could you use educational technologies as a teacher in the classroom to help the students overcome their difficulties? Give reasons for your answer, please.", see anonymized link for the entire test items). Additionally, the participants had to provide an answer whether and how educational technology could help to solve the subject specific teaching problem and to justify their answer. As such, the pre-service teachers would need to apply their pedagogical content knowledge (PCK) and relate it to their technological knowledge (TK) to successfully solve the items. Each test had eight open-ended items. For each item, pre-service teachers could receive three points, resulting in an overall score of 24 points (see Appendix D, for the scoring rubric and examples). Twenty percent of the answers were rated by two subject-matter pedagogy experts. Inter-rater-reliability was good for each test version (*ICC* > .92). Additionally, internal consistency was good (range of Cronbach's α: .72 - .77, except for one TEFL: α = .54, however, see Stadler et al., 2021, for a critical discussion for using Cronbach's α for knowledge assessments).

10.2.3.3 Perceived Support During the Courses for Technology Integration (SQD)

To assess the perceived support for technology integration, we used the SQD-questionnaire by Tondeur et al. (2018). The questionnaire consisted of 22 items (e.g., "In the course, I saw good examples of ICT practice that inspired me to use ICT applications in the classroom myself."; "During the course, I received a great deal of help developing ICT-rich lessons.") The items were answered on a four-point Likert scale ranging from 1 (strongly disagree) to 4 (strongly agree). The internal consistency of the questionnaire was excellent: Cronbach's α = .97.

10.2.4 Procedure

Before the module started, we obtained approval by our local ethics committee. The courses were randomly assigned to the TPACK-module or the control condition. At the beginning of the semester, the pre-service teachers provided written consent to participate in the study. Afterwards, they provided their demographic data and answered the pretest comprising the three motivation scales and the prior knowledge test. After a period of regular teaching in the subject pedagogies, the TPACK-modules were implemented in the last third of the semester. The pre-service teachers in the experimental condition participated in the TPACK-modules. The control condition continued with their regular course instruction without the TPACK-module (business-as-usual condition). The courses were held by certified subject-pedagogy teacher educators. All the teacher educators had ample experience in the context of teacher education and held a teaching certificate for the taught subjects. Particularly, the teacher educators in the TPACK-intervention were explicitly trained to teach the particular modules to ensure implementation fidelity (see also 10.2.5). To prevent experimental leakage across courses, the teacher educators either taught in the control condition or the intervention. At the end of the intervention, the pre-service teachers answered the posttest comprising the three motivation scales, the TPK-posttest, and the TPACK-posttest. The entire study was self-paced and implemented in SoSci-survey.

10.2.5 Implementation Fidelity

To ensure that our TPACK-modules were delivered as intended, we implemented the following safeguards (see Carroll et al., 2007, for an overview). To ensure the adherence of our intervention, we implemented a teaching script for all instructors to keep the courses as comparable as possible. The three instructors had regular exchange to ensure the comparability across courses. For this purpose, at the end of each session, the instructors were asked to answer a self-report questionnaire, in which they assessed, whether they realized the particular teaching activities per session. Across the interventions, all the instructors reported to have realized each of the intended learning activities in the TPACK intervention. Regarding pre-service teachers' exposure to the treatment, the structure of the treatment courses as well as the amount of assignments and activities was kept constant across treatment courses. Overall, 86 % of the participating pre-service teachers attended all the sessions of the TPACK-intervention (cf., coverage, see Carroll et al., 2007). The control courses did not include technology-related content (see also 2.2.1 for more details). Until the beginning of the TPACK-intervention, instruction was comparable across conditions, suggesting that both conditions were exposed to a comparable amount of basic pedagogical-content knowledge. Also the type of instructional methods between the TPACK-intervention and the business-as-usual condition was comparable during the TPACK-intervention, as students in the business-as-usual condition were also engaged in student-centered activities to deepen their knowledge, such as lesson planning, or designing instructional material, however, without the requirement to use educational technologies (see 10.2.2.1, for more details). These findings indicate that implementation fidelity was high, and potential findings may be attributed to content-specific differences between the TPACK-intervention and the control condition.

10.2.6 Statistical Analysis

As our data were nested within subjects and cohorts, we decided to use multilevel regressions to account for the multi-level structure data structure during our analyses (Hox, 2010). Such approaches have frequently been applied in aggregating research data (e.g., in studies across subjects or in individual-participant metanalytic approaches), as they provide more exact likelihood specification, that avoid the assumptions of within-cluster normality and within-study variances (Burke et al., 2017). We used the lme4-package in *R* and applied a varying-slope model to account for the nested structure of our data (Hox, 2010). The models considered pre-service teachers to be nested within subjects, and cohorts, so ‘pre-service teachers’ represented Level 1, ‘subjects’ represented Level 2, and ‘cohorts’ represented Level 3. Condition was included as a fixed dummy-coded effect. Subjects and cohorts were included as random effects. We decided to include the maximal pre-registered multi-level structure instead of following a step-wise integration approach as previous Monte Carlo simulation studies demonstrated that models generalize best when they consider the maximal random effects structure (Barr et al., 2013). The dependent variables comprised pre-service teachers' performance on the knowledge tests (i.e., TPK, TPACK) and their motivation (i.e., self-efficacy, utility-value, teaching enthusiasm). Additionally, we controlled for prior knowledge, and their motivation at the pretest. As prerequisites (i.e., prior knowledge, motivation at pre-test) could vary across pre-service teachers, we allowed the slope of the prerequisites to vary by pre-service teacher per analysis which resulted in the following equation: outcome variable = condition + prerequisite + (1+ prerequisite | cohort/subject).

Additionally, as the intervention was realized in the context of regular teacher education courses, some participants missed the posttest which resulted in missing data. Following recent research, we used multiple imputation (n = 100) and imputed missing values simultaneously (Grund et al., 2016) by applying the R-package *pan* which considers multi-level structures during imputation.

10.3 Results

10.3.1 Preliminary Analyses

A series of multi-level regressions and χ^2 tests revealed no significant differences between the experimental conditions concerning age, β = -0.11, p = .439; gender, $\chi^2(2)$ = 3.12, p = .210; and prior knowledge, β = -0.07, p = .609. Similarly, pre-service teachers' technology-related motivation at the pretest did not significantly differ among conditions, for self-efficacy: β = -0.15, p = .287; utility-value: β = 0.10, p = .458, and teaching enthusiasm: β = -0.06, p = .687 (see Table 17, for the descriptives).

Table 17

Means and Standard Deviations (in Parentheses) for the Dependent Measures

	Control condition	TPACK-Intervention
Knowledge assessments		
Prior knowledge	4.92 (2.45)	4.62 (2.74)
TPK	16.95 (5.00)	15.42 (5.02)
TPACK	8.60 (3.92)	10.21 (3.35)
Motivational assessments		
Self-efficacy pretest	2.47 (0.51)	2.40 (0.51)
Self-efficacy posttest	2.43 (0.46)	2.82 (0.48)
Utility-value pretest	3.25 (0.55)	3.30 (0.49)
Utility-value posttest	3.37 (0.45)	3.28 (0.55)
Teaching enthusiasm pretest	3.23 (0.49)	3.21 (0.46)
Teaching enthusiasm posttest	3.31 (0.47)	3.39 (0.42)
Subjective support	1.92 (0.67)	2.93 (0.45)

Note. The descriptives are based on the raw scores of the dependent measures.

10.3.2 RQ 1: Analyses Regarding Professional Knowledge

A summary of the entire test statistics can be found in the Appendix E. The descriptive statistics can be found in Table 17. Regarding pre-service teachers' technological pedagogical knowledge (TPK), the effect of condition was not significant, β = -0.22, $p = .179$. As such, our hypothesis that the TPACK- modules would outperform the control condition in the TPK-test was not confirmed.

Regarding pre-service teachers' technological pedagogical content knowledge (TPACK), in line with our hypothesis, we found that the TPACK- modules outperformed the control condition, β = 0.45, $p = .002$. The effect of the TPACK- modules was of medium size, as the acquired TPACK in the intervention was 0.45 standard deviations higher than in the control condition.

10.3.3 RQ 2: Analyses Regarding Technology-Related Motivation

Regarding pre-service teachers' technology-related self-efficacy, again, we obtained a significant effect of the TPACK-modules, $\beta = 0.81$, $p < .001$. This finding indicates that after the TPACK-modules, pre-service teachers possessed higher levels of technology-related self-efficacy (0.81 standard deviations) than the control condition. The effect of the TPACK-modules, however, was not significant for the perceived utility, $\beta = -0.17$, $p = .274$, and also not significant for technology-related teaching enthusiasm, $\beta = 0.21$, $p = .161$. As such, our motivation hypotheses were partially confirmed, as the TPACK-modules only contributed to pre-service teachers' self-efficacy but not to the perceived utility nor teaching enthusiasm.

10.3.4 RQ 3: Analyses Regarding the Perceived Subjective Support

Regarding the perceived subjective support during the intervention, again, we obtained a significant effect of condition, $\beta = 1.39$, $p < .001$. This finding suggests that when pre-service teachers were participating in the intervention condition, they perceived the obtained support regarding technology integration to be 1.39 standard deviations higher than in the control condition.

10.3.5 Explorative Mediation Analyses

As students in the TPACK-module showed greater TPACK, technology-related self-efficacy, and perceived support, we explored, whether the differences in TPACK and technology-related self-efficacy could be explained via the perceived support for technology-integration during the TPACK-modules. We conducted two multi-level mediation analyses separately for TPACK and technology-related self-efficacy via the mediation package implemented in R. Condition was the predictor, perceived support the mediation variable. TPACK and technology-related self-efficacy were the dependent variables. We used 1,000 simulations to derive a 95%-bias-corrected confidence interval for the indirect effects. Our findings did not support the idea that perceived support was a mediator for technology-related self-efficacy, as the indirect effect was not significant, a × b = 0.00, $p > .999$. However, we obtained a significant unstandardized indirect effect for TPACK, a × b = 1.80, $p < .001$, suggesting that part of the effect of the intervention on TPACK could be explained by pre-service teachers' perceived support for technology-integration.

10.4 Discussion

The aim of the current study was to examine the effects of an evidence-based intervention (i.e., TPACK-modules) to foster pre-service teachers' technology-related professional knowledge and technology-related motivation. In line with our hypotheses regarding pre-service teachers' professional knowledge, we found that the intervention condition outperformed the control condition regarding their acquisition of subject-specific technological pedagogical content knowledge (i.e., TPACK) but not regarding generic technological pedagogical knowledge (i.e., TPK). As our intervention was specifically designed as a subject-specific intervention, a possible explanation could be that it was difficult for pre-service teachers to generalize their subject-specific knowledge to generic teaching situations, which is a typical problem in instructional research (see Barnett & Ceci, 2002; Goldwater & Schalk, 2016). Regarding pre-service teachers' motivation, we obtained a significant effect of our intervention on self-efficacy as the intervention condition demonstrated higher levels of self-efficacy than the control condition. However, contrary to our hypotheses, we did not obtain significant effects of the intervention on the perceived utility-value and technology-related teaching enthusiasm. This finding likely resulted as our pre-service teachers already reported high levels of utility of technology and teaching enthusiasm at the beginning of the intervention suggesting that the non-significant findings may be attributed to ceiling effects in the experimental conditions. Given that motivation is a multifaceted construct, comprised of potential interactions among different constructs, it would be a potential path for future research to map a broader picture about the development of teacher motivation by including different approaches (Ryan & Deci, 2003) or testing a broader set of variables, as proposed by broader models, such as TAM-models (Teo, 2011). As indicated by our mediation analysis, a potential explanation for why our intervention was effective is that pre-service teachers perceived higher levels of subjective support to integrate technology, which contributed to their professional knowledge acquisition. Since we deliberately implemented our TPACK module based on recent principles derived from teacher education (Grossman et al., 2009; Tondeur et al., 2012), students received higher levels of support which contributed to their professional knowledge acquisition.

What are the theoretical insights of our intervention? As a first contribution, we claim that our intervention is one of the first empirical attempts which explicitly tested the potential of evidence-based and theoretically grounded interventions in a subject-specific and quasi-experimental manner in real-world contexts. The scarcity of such interventions is surprising as Mishra and Koehler (2007) already highlighted the role of fostering TPACK for future technology integration. We strictly designed our intervention based on general principles of teacher education (Grossman et al., 2009) and specific guidelines for supporting technology integration (Tondeur et al., 2018). As we realized a quasi-experimental field study and randomly assigned individual courses to our experimental conditions, we can make distinct conclusions about the role of the availability of such implementation features on the acquisition of TPACK and self-efficacy. Although our mediation analyses supported this claim, that it was the perceived support which explained the effectiveness of the TPACK-module (at least for the acquisition of TPACK), it is an open question, however, how much of which feature of the module accounted for pre-service teachers' TPACK. Therefore, more granular studies are needed which experimentally investigate the single benefits of the instructional constituents regarding TPACK.

A further strength of our study was that we designed and applied test-based instruments to assess pre-service teachers' TPACK, given that most previous research relied on self-reports (e.g., Tondeur et al., 2018) or generic instruments which roughly ignored the subject-specific character of TPACK (Kramarski & Michalsky, 2010; Lachner et al., 2019). Our test-based instruments were constructed by an interdisciplinary team to heighten constructive validity. Furthermore, the findings demonstrated satisfactory reliability. Put differently, we also obtained significant overall effects of our intervention by means of our instrument, indicating the prognostic validity of our test-based instruments. However, more research is needed to further explore the adequacy of our TPACK-tests as diagnostic instruments.

As a practical implication, the intervention can be used to further develop subject-specific interventions. Against this background, all the materials can be downloaded as Open Educational Resources (see anonymized link) which may facilitate the adoption of our intervention in teacher education programs. As such, we hope that our interventions can serve as a fruitful starting point for the further development of subject-specific interventions.

Besides the potential of our findings, there are also some limitations. In our study, we realized a classical effectiveness study (e.g., Herbein et al., 2018) and analyzed pre-service teachers' cognitive and motivational outcomes. Such studies on the one hand allow to test the applicability and effectiveness in an authentic and ecologically valid setting. However, such settings do not allow to examine fine-grained analyses about the potential underlying learning processes. Therefore, more research is needed to investigate the learning processes during such an intervention. We also did not examine delayed knowledge tests, which would allow to test for long-term effects of our intervention.

Another issue regards the decision to implement the TPACK-modules in five different subjects comprising different approaches to integrate technology and different subject-matter pedagogies. To ensure comparability among subjects, we aimed to implement the same structure across subjects. Additionally, the instructors in the TPACK-modules regularly interacted with each other to ensure that the modules were as comparable as possible. This approach was also reflected in the data-analysis approach, as we included subjects and cohorts as random factors to determine whether such an intervention has an overall effect across different subjects. Therefore, we rather see this potential limitation as a type of robustness check of the intervention. Nevertheless, a replication with likely a larger number of participants and ideally realized as a true experimental study would be desirable to draw legitimate causal judgments regarding the effectiveness of the TPACK-modules. Furthermore, some emphasis on further improving our applied test instruments, particularly the TPK-tests and the self-efficacy ratings would help provide more reliable estimates of our outcomes.

Finally, another limitation of the study regards the potential confounding difference in cohort 2 due to the switch from face-to face to online teaching as compared to cohort 1. Students in the control condition were also exposed to online teaching and could have acquired technological knowledge regarding potential technologies in addition to pedagogical content knowledge. These circumstances could have somewhat lowered the effectiveness of our intervention. However, we want to note that we considered this potential effect in our analyses as we included the cohort as a control variable in our analyses.

Our study provides important evidence regarding the effective design of instructional interventions to foster pre-service teachers' TPACK and self-efficacy. TPACK and self-efficacy can be regarded as important prerequisites for pre-service teachers to successfully integrate technology during their subject specific teaching. As such, our findings may help improve the quality of technology-enhanced teaching.

.

10.5 Appendix D

Table 18

Scoring Rubric for the TPACK Assessments

Categories	Description	Sub-categories	Example
Instructional quality (based on Backfisch et al., 2020)	In this category we assessed whether the pre-service teachers were able to apply educational technologies to improve instructional quality (i.e., cognitive activation, instructional support, classroom management) in the given subject-specific teaching scenario.	0 points = The code was assigned if no answer was given or if it was hardly plausible how the selected educational technologies could contribute to the instructional quality.	„*Use online learning programs*“
		0.5 points = The code was assigned if it was partially plausible how the selected educational technologies could contribute to the instructional quality.	„*Online voting methods or surveys such as Mentimeter show the frequency of the answers given (possibly represented by pie charts or similar)*”
		1 point = The code was assigned if it was completely plausible how the selected educational technologies could contribute to the instructional quality.	„*Texts could be hyperlinked in digital form to break down allusions or difficult phrases. Difficult text passages could be supplemented by clusters so that an associative approach to the passages is possible*.”
Quality of technology exploitation	In this category, we assessed whether the pre-service teachers were able to exploit the innovativeness of the applied technology.	0 points = The code was assigned if the selected educational technology only substituted traditional approaches to implement same teaching/learning methods and to achieve same	„*As a start, you could show a video on the video projector.* “

		learning objectives (**R**eplacement).	
		0.5 points = The code was assigned if the selected educational technology replaced traditional technology with functional improvement or efficiency increase (**A**mplification).	„*The students could use writing programs such as Good Notes. Here it would be possible to split the screen so that the students can directly note down the most important facts in Good Notes.*“
		1 point = The code was assigned if the selected educational technology allowed the implementation of previously unfeasible learning and teaching methods or when completely new learning objectives can be achieved (**T**ransformation).	„*Natural selection is a long-lasting process, which therefore cannot be tracked. With a simulation in which, for example, the color of the wings and the environmental conditions can be varied, the students could conduct virtual experiments on the topic. This contributes to a deeper understanding.*”
Quality of the justification (Schäfer & Seidel, 2015)	In this category, we assessed whether the pre-service teachers were able to justify, why the selected educational technologies could improve the instructional quality or how the distinct functions of the selected educational potentially support students learning processes in the given subject specific teaching scenario.	0 points = The code was assigned if there was no justification or an incorrect justification.	„*Students could search the Internet for information about the topic and use that information to write an argumentative essay. The internet search allows the students to have more prior knowledge about the topic.*“
		0.5 points = The code was assigned if there was a non-	„Again, a program like GeoGebra would be very helpful, simply

	scientific (i.e., subjective theories, anecdotal evidence) justification.	because then the necessity of the own construction is omitted first and the pupils can concentrate on the task without having to draw every time.”
	1 point = The code was assigned if there was an evidence-based (i.e., scientific theories or models, or empirical evidence) or simplified scientific (e.g., plain explanations about mental processes) justification.	„[…] *Another way to get to know the different cycles would be to divide the students into small groups and let them create an educational video for one cycle each, so the students are forced to deal intensively with their cycle themselves as "experts", a subsequent merging of the cycles is facilitated*.“

10.6 Appendix E

Table 19

Model Parameters from the Multilevel Analyses of our Dependent Measures

TPK	Estimate (*SE*)	*p* (two-sided)	FMI
Intercept	0.03 (0.211)	.900	0.055
Condition	-0.221 (0.162)	.172	0.322
Prior knowledge	0.255 (0.128)	.047	0.241
$Var(\upsilon_{0j})$	0.008		
$Var(\varepsilon_{ij})$	0.853		
TPACK	Estimate (*SE*)	*p* (two-sided)	FMI
Intercept	-0.226 (0.171)	.185	0.062
Condition	0.444 (0.144)	.002	0.217
Prior knowledge	-0.146 (0.106)	.169	0.291
$Var(\upsilon_{0j})$	0.191		
$Var(\varepsilon_{ij})$	0.717		
Self-Efficacy	Estimate (*SE*)	*p* (two-sided)	FMI
Intercept	-0.320 (0.119)	.007	0.106
Condition	0.804 (0.141)	< .001	0.268
Self-efficacy (pre)	0.359 (0.083)	< .001	0.211
$Var(\upsilon_{0j})$	0.024		
$Var(\varepsilon_{ij})$	0.690		
Utility value	Estimate (*SE*)	*p* (two-sided)	FMI
Intercept	0.099 (0.137)	.467	0.132
Condition	-0.171 (0.155)	.268	0.341
Utility value (pre)	0.442 (0.103)	< .001	0.208
$Var(\upsilon_{0j})$	0.007		
$Var(\varepsilon_{ij})$	0.769		
Teaching enthusiasm	Estimate (*SE*)	*p* (two-sided)	FMI
Intercept	-0.088 (0.118)	.499	0.135
Condition	0.205 (0.148)	.167	0.329
Teaching enthusiasm (pre)	0.500 (0.109)	< .001	0.108
$Var(\upsilon_{0j})$	0.010		
$Var(\varepsilon_{ij})$	0.718		
Perceived Support[1]	Estimate (*SE*)	*p* (two-sided)	FMI
Intercept	-0.618 (0.106)	< .001	0.071
Condition	1.383 (0.116)	< .001	0.172
$Var(\upsilon_{0j})$	0.051		
$Var(\varepsilon_{ij})$	0.515		

Note. Estimates are standardized *b*-coefficients; FMI = fraction of missing information; var(υ_{0j}) = random intercepts; ε_{ij} = residuals. [1]For perceived support, no control variable at the pre-test was included.

11 General Discussion

Developing students‘ mathematical knowledge is vital in today’s society (e.g., Kollosche et al., 2023). Recognizing both, the potentials of technologies in supporting students’ mathematical learning and the difficulties implementing them, professional knowledge of teachers has been discussed as a crucial pre-requisite for high-quality teaching with technologies. Such knowledge has been prominently conceptualized via the TPACK-model by Mishra and Koehler (2006). Although TPACK is a vivid and stimulating framework in research and practice, a mathematics-specific examination of TPCK (i.e., the central TPACK-component) has been lacking to date. Therefore, the present dissertation sought to fill this research gap by pursuing three overarching research goals which were addressed in the course of three studies.

The first overarching goal was to investigate how TPCK has been conceptualized and assessed to date in educational research (study 1), extending the scope beyond mathematics. The second overarching goal was to investigate the inherent structure of mathematics-specific TPCK (study 2). To do so, I developed and validated a test-based instrument that assesses mathematics-specific TPCK. The third overarching goal was to develop an evidence-based and mathematics-specific intervention aimed at fostering pre-service mathematics teachers’ TPCK, evaluating its effectiveness based on the self-developed test instrument.

11.1 Summary of Studies

In the first study, I conducted a systematic review based on a rich set of primary studies (N = 166 interventions) and investigated existing conceptualizations of TPCK by examining how TPCK has been fostered in interventions to date. By focusing on the design of interventions, I was able to deduce in detail which TPACK-components (i.e., TK, PK, CK, TPK, TCK, PCK, TPCK) researchers deemed necessary for the acquisition of TPCK allowing insights into their perspective on TPCK (as rather pedagogical, technological or subject-specific, see 4.3). For the purpose of this review, I adopted a broad approach, not limited to mathematics, to examine how TPCK has been conceptualized across different subject domains. Moreover, in study 1, I conducted a subsequent meta-analysis based on studies applying performance-based measures (*N* = 8) to examine the overall effectiveness of prior TPACK-based interventions which extends prior meta-analyses that were based predominantly on self-report studies. The main insights gained from the first study were that most researchers seemed to have viewed TPCK from a rather technological angle as indicated by the high percentages of interventions specifically targeting TK. Interestingly, TPCK as the main objective of these interventions has only been specifically focused in roughly 80 %. Framed differently, in only 80 % of the interventions, the (pre-service) teachers were exposed to opportunities in which they could practice integrating different knowledge components to learn how to use technologies effectively in subject-matter teaching. Regarding the assessment of TPCK, the results of the review indicated a predominant use of self-report measures which is in line with previous findings (Koehler et al., 2012; Willermark, 2018). Moreover, only a very limited number of studies evaluated the effectiveness of interventions by means of a research design that allows to investigate knowledge growth. As a result, my meta-analysis sample comprised of only *N* = 8 studies. These studies generally indicated that TPACK-based interventions were highly effective in improving (pre-service) teachers' TPCK. However, the limited number of studies included in the meta-analysis highlights the field's shortfall in employing more robust research designs to track knowledge growth which I consider the main finding of the meta-analysis.

For study 2, I thoroughly conceptualized mathematics-specific TPCK (see 4.4). This knowledge extends mathematics-specific PCK by incorporating an understanding of the capabilities and benefits of various technologies for mathematic-specific instruction. In study 2, I applied validated and test-based instruments in an online study to investigate the inherent structure of mathematics-specific TPCK, that is, TPCK and its relationship to mathematics-specific PCK and TK. In doing so, I extended prior research by considering TPCK from a mathematics-specific angle including PCK in the analysis. Moreover, I employed a self-reported TPCK questionnaire to investigate possible influencing variables that may account for the weak relationship between test-based and self-reported TPCK. These variables included participants' demographics such as age and gender, as well as participants' ability to accurately assess their own knowledge following general metacognitive research (Flavell, 1979). Main insights from the study are that mathematics-specific TPCK and mathematics-specific PCK seem to be related yet distinct knowledge components, and that both PCK and TK contributed statistically equally to TPCK. Furthermore, pre-service teachers' metacognitive accuracy moderated the statistical relationship between self-reported and test-based TPCK indicating that self-report questionnaires are suitable for evaluating objective TPCK if and only if participants are able to accurately assess their own knowledge, thereby confirming prior assumptions (e.g., Abbitt, 2011) empirically.

Finally, the third study dealt with the question of how (and whether) it is possible to develop pre-service teachers' TPCK in the context of short interventions implemented in subject-specific PCK University courses. The main insights gained through this study are that it is indeed possible to enhance mathematics-specific knowledge for technology integration through brief modules that are grounded in theory, empirical evidence, and that are tailored to mathematics-specific considerations. Moreover, in this study, I further considered motivational variables, such as self-efficacy and utility-value, given that motivation has been shown to be a significant predictor for TPCK (Backfisch et al., 2020; Ertmer & Ottenbreit-Leftwich, 2010). The findings of the third study demonstrated that the pre-service teachers from the TPACK-modules increased their utility value significantly more than those from the control group. In contrast, self-efficacy was not positively affected by the TPACK-modules. Another crucial finding from the third study is that the subjective support in the TPACK-modules mediated the effect of the condition on TPCK indicating that participants require ample support, such as constant feedback, to acquire TPCK.

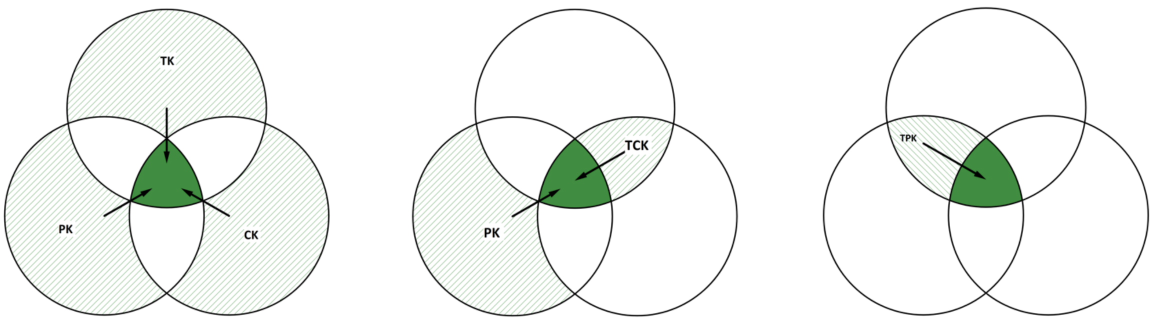
11.2 Theoretical Implications

11.2.1 How has TPCK been Conceptualized in Prior Research Across Subjects?

What are the theoretical implications of my dissertation? Regarding research question 1 (i.e., conceptualizations of TPCK across subjects), TPCK seems to have primarily being viewed or approached from a technocentric perspective given the mass of interventions specifically targeting basic knowledge about how to operate with technologies (i.e., TK). Furthermore, a significant number of researchers who professed to have developed their interventions on the TPACK-model appear to have not fully implemented it, as evidenced by the neglect of TPCK – the model's core element – in approximately 20% of cases. If TPCK is of transformative nature, the involvement in these studies could create substantial challenges for the participating (pre-service) teachers in attaining TPCK. This is because TPCK, viewed from a transformative perspective as a distinct knowledge component, does not evolve merely by enhancing other TPACK-components (Angeli et al., 2016). This is especially pertinent when considering the need for explicit guidance in intervention studies for the effective acquisition of TPCK as indicated by the findings of the intervention study (i.e., study 3). Moreover, the findings of study 1 revealed a lack of consensus among scholars regarding the interpretation of the TPACK-model, despite its widespread recognition in both academic and practical contexts. This does not negate the model's capacity for evolution in response to advancements in technology and pedagogy. Yet, it is noteworthy that many researchers within the TPACK community frequently seemed to have employed and modified the model without explicitly defining their conceptual understanding of it. In particular, researchers have often not specified their viewing angle on TPCK (i.e., pedagogical, technological, or subject-specific), nor did they clarify the theoretical underpinnings of TPCK as either transformative or integrative. This jangle-fallacies (i.e., labeling different concepts the same way, see study 1) makes it difficult for practitioners and researchers alike to compare and build upon prior research findings. In this light, I encourage future researchers to clearly indicate how their approach to conceptualize (and foster) TPCK is related to the other TPACK-components (i.e., TK, CK, PK, PCK, TPK, and TCK), thereby clarifying their viewing angle on TPCK as well as their understanding of TPCK as either transformative or integrative. This is not to suggest that I advocate for developing another, new TPACK-model. Rather, I align with the position of Angeli et al. (2016) who argued “there are already enough TPCK frameworks, or variations of them, in the literature, and that no more research efforts and resources should be invested towards this direction” (p. 23). Therefore, I propose updating the commonly used TPACK Venn diagram (Mishra & Koehler, 2006) by including arrows that clearly indicate the *viewing angle of* or *path to* TPCK (Cox & Graham, 2009). Emphasizing TPCK in these diagrams as the central component might be a further helpful in highlighting the central role of TPCK when it comes to effective subject-specific technology integration. Figure 15 combines these ideas.

Figure 15

Updated Venn Diagrams to Clearly Indicate from which Angle TPCK is being Approached



Note. In the left diagram, TPCK is approached by basic knowledge components only. In the center diagram, TPCK is approached by prominently focusing on a second-order knowledge component (here TCK) combining it with a basic knowledge component (here PK). In the right diagram, TPCK is approached by primarily addressing TPK, neglecting subject-specific knowledge about technology integration.

11.2.2 Mathematics-Specific TPCK: Its Relationship to TK, Mathematics-Specific PCK and the Validity of Self-Reported Instruments

Regarding researching question 2 (i.e., the inherent structure of mathematics-specific TPCK), two main results significantly contributed to the understanding of TPCK's theoretical underpinnings. First, while PCK and TPCK are moderately related, they still seem to be distinct knowledge components mirroring findings about the empirical distinguishability of PCK and CK (Krauss et al., 2008). Therefore, the theoretical distinction between PCK and TPCK seem to be warranted despite existing conceptualizations that consider TPCK merely a sub-facet of PCK (Cox & Graham, 2009; Schubatzky et al., 2023). Second, the results of study 2 further suggested that PCK and TK are both necessary knowledge components of technology-enhanced instruction in mathematics teaching. At the same time, PCK and TK could not explain the whole variance of TPCK indicating that TPCK goes beyond the mere integration of PCK and TK. This may be suggestive of TPCK being of transformative nature which would be in line with recent findings from the discipline of biology education (von Kotzebue, 2022). At the same time, however, the relatively equal amount of explained variance of TK and PCK in TPCK speaks against the transformative nature of TPCK when considering Schmid et al.'s (2020a) and von Kotzebue's (2022) empirical operationalization of the transformative view (see 4.2).

Another crucial theoretical implication of study 2 is the dependency of participants' metacognitive accuracy on the relationship between test-based and self-reported TPCK providing first empirically validated insight into the low relationships between both assessment methods prevalent in the TPACK literature (Drummond & Sweeney, 2017; Max et al., 2022; von Kotzebue, 2022). This finding could offer an initial explanation for the heterogeneity of earlier research examining relationships between TPACK-components using mostly self-reported data. Put differently: The validity of Self-Reports TPCK instruments to assess mathematics pre-service teachers' hinges on pre-service teachers' metacognitive ability to accurately assess their own TPCK. However, due to the novel nature of study 2 in considering metacognitive accuracy, additional research is essential to replicate and expand upon these findings. Potentially, developing more contextually situated self-report items might be a path towards increasing their validity. To elaborate, in developing and employing self-report instruments featuring items embedded in specific scenarios, like the use of technology in real-world, mathematics-specific classroom situations, may enable teachers to assess their own knowledge more accurately, and therefore increase the validity of self-reported instruments as suggested recently by Sailer et al. (2021).

Consequently, I endorse the widespread recommendations to combine different assessment approaches for a more comprehensive perspective on mathematics-specific TPCK (Abbitt, 2011; Kopcha et al., 2014; Willermark, 2018).

11.2.3 Fostering Pre-Service Teachers Mathematics-Specific TPCK

Regarding research question 3 (i.e., how to foster mathematics-specific TPCK within a three-week module), the findings highlight the potential to foster mathematics-specific TPCK effectively over a short period of time, provided the interventions are structured in line with evidence-based principles from mathematics education and generic technology education. Moreover, the findings highlight the importance of guidance for pre-service teachers in acquiring such knowledge and therefore underlines the significance of teacher educators who follow evidence-based research (Slavin, 2020).

11.3 Practical Implications

The practical implications of the findings of this dissertation are significant and multifaceted, particularly regarding the design of effective pre-service teacher training. To start with, as TPCK and PCK are distinct knowledge components as suggested by study 2, pre-service teacher training programs need to incorporate a deeper and more nuanced understanding of TPCK that adheres to the transformative view. This means designing curricula that transcend PCK and basic technological skills (i.e., TK), focusing instead on the effective integration of technology with a focus on mathematics-specific peculiarities. In particular, based on my findings, I recommend against treating PCK and TK as separate entities in the design of effective curricula but instead emphasize their fusion into TPCK that goes beyond both knowledge components. In other words: technology should be considered an integral part in pre-service teacher training in mathematics. My argument echoes those of researchers who argued against promoting TPCK in isolated technology-centric courses and instead promoting TPCK in an integral approach (Angeli et al., 2016). To give an example, modules that address knowledge on how to teach the Pythagorean Theorem and how to operate with GeoGebra separately seem insufficient. Instead, (pre-service) teachers require ample training opportunities that combine those separate knowledge elements, by reflecting on GeoGebra' advantages (and disadvantages) and its "added value" (Angeli & Valanides, 2009, p. 167) for the *specific purpose* of enhancing students' conceptual understanding of the Pythagorean Theorem. Only then, pre-service teachers are likely to reach mathematics-specific TPCK, the central pre-requisite for providing high-quality instruction with technologies in mathematics.

Additionally, this dissertation introduced a reliable and valid approach for assessing mathematics-specific Technological Pedagogical Content Knowledge (TPCK) in an *objective* way, offering educators world-wide a tool to evaluate the effectiveness of their courses designed to enhance knowledge for technology integration. Also, study 2 highlights the need to take into account the metacognitive accuracy when developing pre-service teachers' knowledge of technology integration. The more accurately pre-service teachers can assess their own knowledge, the more effectively they can direct their development of TPCK (Max et al., 2022). To improve metacognitive accuracy of pre-service teachers, it is recommendable to provide constant opportunities in which pre-service teachers can regularly compare what they think they know to what they actually know. Such opportunities, commonly referred to as formative assessments (Harlen & James, 1997), might include brief tests for assessing their grasp of concepts or the use of reflective diaries (Backfisch, Lachner et al., 2021).

Moreover, the results of study three highlight the crucial role of experienced educators as teachers. These educators can act as a role model, provide guidance and support, helping pre-service teachers to navigate the complexities of integrating technology effectively in their future classrooms. In addition, training programs should include evidence-based, and flexible teaching strategies that are responsive to the fast-evolving landscape of new technologies. With the recent availability of artificial intelligence for educational purposes (e.g., Kasneci et al., 2023), the need for such responsiveness and flexibility becomes even more relevant.

Overall, the findings of the dissertation suggest a shift towards more integrated, reflective, and research-informed approaches in preparing pre-service teachers for their future life as practicing mathematics teachers.

11.4 Strengths and Limitations

The present dissertation capitalizes on multiple strengths. First, I adhered to good scientific practices as I pre-registered each study, confirmed to data protection laws and set high ethical standards in conducting the studies. Second, a total of three studies provided a comprehensive overview on the complex topic of mathematics-specific knowledge teachers need for high quality technology integration. In particular, I have built upon findings from generic research of technology education (i.e., the TPACK-model; Mishra and Koehler, 2006) and combined it with the rich insights gained from research on the potentials of technology use in mathematics education (Bray & Tangney, 2017; Cevikbas et al., 2023; Engelbrecht & Borba, 2023; Molina-Toro et al., 2019; Olive et al., 2009). By integrating both research strands, this dissertation is the first work to thoroughly examine knowledge of mathematics teachers with a specific focus on technology integration, thereby extending the rich research on mathematics-specific PCK. Third, I combined several methodological approaches to answer the research questions. These methods included a systematic review which adhered to the high standards of the PRISMA framework (Page et al., 2021), a meta-analysis guided by best practice (Borenstein et al., 2009; Harrer et al., 2022), and the implementation of sophisticated research designs such as a planned missing data design (Graham et al., 2006) or a ManyClasses approach (Fyfe et al. 2021). Additionally, analyses were performed using advanced techniques like Rasch models and multilevel-random effect models to obtain robust empirical evidence for the suggested claims. Fourth, although my primary focus was on the construct of knowledge, I integrated several other variables throughout my studies deemed essential in TPCK acquisition and assessment, including motivation (such as self-efficacy beliefs and utility-value), metacognitive competences, and participants' demographics. This broad approach acknowledged the importance of context inherent to the TPACK-model (Brianza et al., 2022; Mishra, 2019).

At the same time, I acknowledge several limitations of my dissertation. First and foremost, I assessed TPCK from a merely cognitive perspective (Baier & Kunter, 2020) which is knowledge detached from the actual performance in the classroom (cf. formal knowledge, Fenstermacher, 1994). Therefore, it is unclear to what extent the findings based on my TPCK test (or PCK and TK) would translate to skills in the actual act of teaching (Brantley-Dias & Ertmer, 2013; see 4.1). The second limitation, closely related to the first one, emerges from study 3 where I fostered mathematics-specific TPCK in gradually more authentic settings (ranging from acquiring knowledge through a learning module to slip into the role of teachers withing micro teachings, see 6.2), thereby mostly focusing on TPCK as skill. At the same time, however, I evaluated the effectiveness with a test-based instrument, thereby exclusively focusing on TPCK as knowledge (see 4.1). Possibly, this discrepancy between fostering TPCK as a practical skill and assessing it as knowledge have led to biased results (cf. Willermark, 2018) and therefore presents a limitation. The third limitation refers to my conceptualization of TPCK. Although covering aspects most relevant for knowledge regarding the didactical integration of technologies into mathematics, I did not include knowledge on ethical aspects that the use of technologies brings along (e.g., data protection) when conceptualizing TPCK, something that just recently found its way into TPACK-related research (Celik, 2023). Such aspects are becoming particularly relevant with the advent of AI-based technologies in education., and include – among others (see Celik, 2023, for an overview) – knowledge of how sensitive data of students are stored (Fütterer et al., 2023), or knowledge about how language models are trained resulting in the reproduction of discriminating behavior (e.g., De Cremer & De Schutter, 2021). Therefore, future researchers should incorporate ethical considerations into the conceptualization, assessment and development of (pre-service) teacher's TPCK. Fourth, although having considered many different variables which have been deemed importance in the context of TPACK throughout my dissertation, the scope of the dissertation forced me to ignore several others which are likely to be related to TPCK, too, leaving room for future research. For example, teachers' level of expertise has been shown to be a decisive factor for the availability of PCK (Krauss et al., 2008) and TPCK (Backfisch et al., 2020). Given the focus on pre-service teachers in my studies, however, I was not able to investigate expertise differences. Another variable I did not consider was related to epistemological beliefs pertaining to the nature of mathematical knowledge and learning (i.e., mathematics as static or dynamic, see Thurm et al., 2023, for an overview). Possibly, the quality of instruction (and therefore the TPCK score assessed by my test) would vary across participants with different beliefs (see also Weinhuber et al., 2019, for the related effect of mindset on instructional approaches to teach mathematics). Fifth, one needs to keep in mind that the findings of study 2 (i.e., the inherent structure of TPCK) were based on a correlational design and therefore causal claims should be avoided. For example, whether higher levels of mathematics-specific PCK and generic TK automatically translate to higher levels of mathematics-specific TPCK is still questionable due to the correlational design of study 2. Put differently, it is not clear whether instruction on PCK and TK would automatically result in pre-service teachers' acquisition of

TPCK. Sixth, I operationalized TK to be knowledge on operation with technologies (e.g., knowledge about the functions of spreadsheet) following closely Mishra and Koehler's understanding of this knowledge component. Assessing TK in such a way, however, bears the risk to consider specific technologies which may be up to date now, but not in the future. Therefore, future technologies that may find their way into classrooms soon (i.e., virtual reality or AI-based technologies) were not considered (Fütterer et al., 2023). Hence, I encourage future researcher to build upon the present TK test to include such technologies acknowledging the fast-evolving nature of today's digitized society. Finally, the effectiveness of my mathematics-specific three-week intervention was investigated within a larger project consisting of more interventions from several subject-domains. It was not possible to investigate the effectiveness of my intervention based on the limited number of participants in my mathematics-specific intervention. Thus, further research is necessary with larger sample size to ensure statistical power so that the effects of the mathematics-specific intervention can be clearly separated from those associated with the other subjects.

11.5 Conclusion and Outlook

The present dissertation extends the rich body of research on mathematics-specific teaching knowledge (Baumert et al., 2010; Baumert & Kunter, 2013; Blömeke & Kaiser, 2014; Hill et al., 2004; Krauss et al., 2008) by specifically acknowledging the central role of technologies in today's mathematics classrooms (KMK, 2023).

The present dissertation focused on three overarching research goals that pertained to how mathematics-specific TPCK could be conceptualized, assessed and fostered. Major findings of my dissertation were (1) that TPCK has been viewed from a rather technocentric perspective across subject domains, (2) that mathematics-specific TPCK is a unique knowledge component which is distinct from, yet related to PCK, and (3) that short-time interventions designed on evidence-based principles both from educational research and from mathematics education can be effective in fostering pre-service teachers' mathematics-specific TPCK.

In light of the discussed shortcomings, future research possibilities in this field are immense and could further generate insights into mathematics-specific TPCK pushing the field forward. For example, to investigate whether TPCK is a unique knowledge component that does not automatically arise when developing PCK and TK separately (i.e., TPCK as transformative), one could apply a robust research design that allow for causal interpretations. To give an example, one could vary the level of training on PCK, TK and TPCK by randomly splitting a group of mathematics (pre-service) teachers into two groups and provide one group with instruction on TPCK only, and provide the other one with instruction targeting PCK and TK separately, but not TPCK (see Evens et al., 2018, for a related approach on mathematics-specific PCK). To economically conduct such a study, however, the present TPCK instrument is unfeasible due to the economic effort in coding the open-ended answers. Therefore, I encourage researchers to build upon my test instrument and develop an assessment method based on closed response formats, such as multiple-choice items. This would be helpful for studies with large sample sizes (see Große-Heilmann et al., 2023, for first reliable test-based instruments based on multiple choice items in the context of physics education). To generate such items, levering on the responses collected from my open-ended test (study 2) could serve as an effective starting point. At the same time, TPCK is more than formal knowledge applied in standardized testing scenarios which should be acknowledged in the future. Here, the increasing rise of innovative technologies hold the potential to assess TPCK in more authentic, teaching-related settings without the economic restrictions posed by conducting studies in real classrooms. For example, in virtual realities, the quality of mathematical instruction with technologies could be observed directly in the act of teaching, thereby offering the possibility to assess (pre-service) teachers' TPCK as they transform their knowledge into practice (Hwang et al., 2023), acknowledging a “process-oriented perspective on technology integration” (Lachner et al., 2024, p. 4).

Finally, I advocate for increased research on the link between mathematics teachers' ability to integrate technologies and the level of teaching quality as evidenced by students’ learning outcomes. This relationship is of particular importance because – in the end – research in mathematics education should thrive to investigate how to best assist students in developing a comprehensive understanding of mathematics, and thereby increasing the likelihood of reversing the current trends in PISA.

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