Education and Information Technologies
https://doi.org/10.1007/s10639-023-12212-7

Preservice teachers' professional knowledge for ICT integration in the classroom: Analysing its structure and its link to teacher education

Sandra Heine[1] · Matthias Krepf[1] · Daniela J. Jäger-Biela[1] · Kristina Gerhard[1] · Rebecca Stollenwerk[1] · Johannes König[1]

Received: 21 June 2023 / Accepted: 8 September 2023

Abstract
As digitalisation is becoming increasingly important in educational settings, teachers' key competencies – in particular, their professional knowledge regarding the integration of information and communication technology (ICT) in the classroom – warrant targeted development. Aside from their general pedagogical knowledge (GPK), teachers' technological pedagogical knowledge (TPK) and technological knowledge (TK) are becoming increasingly necessary for mastering professional teaching-related tasks (as outlined in the well-known technological pedagogical content knowledge (TPACK) model). To date, however, the question of whether these knowledge facets are discrete or interrelated – at least, on the basis of standardised assessments – has remained largely unanswered. In the present study, therefore, a sample of 619 preservice teachers (320 bachelor's and 299 master's students in their second semesters) were considered via an online survey with three different knowledge tests. In this article, we investigate hypotheses concerning the structures of those knowledge facets and further hypothesise that initial teacher education learning opportunities relate to preservice teachers' GPK, TPK, and TK. Our findings reveal that the three knowledge facets can be empirically separated. Master's students outperform bachelor's students in all three tests, however, with effects varying from strong (GPK) to medium (TPK, TK). As expected, pedagogical learning opportunities – surveyed through students' self-reports – directly correlate with GPK. By contrast, technological pedagogical and technological learning opportunities are not correlated with TPK and TK, respectively. We discuss the findings' implications for future initial teacher education design – in particular, the evident need to update the curriculum to meet the needs of the current era of digitalisation.

Keywords Digitalisation · General pedagogical knowledge · Teacher education · Technological knowledge · Technological pedagogical knowledge · Opportunities to learn

Extended author information available on the last page of the article

Published online: 16 October 2023

1 Introduction

The advancement of digitalisation has posed new and increasing challenges for the teaching profession. Students must be trained in the so-called ‘four C’s’ (critical thinking, communication, cooperation, and creativity) as overarching competencies in addition to mastering digital literacy skills in preparation for life in an increasingly digital society (SWK, 2022), as summarised, for example, in the ‘Key Competences for Lifelong Learning’ (European Commission, 2019). Further frameworks emphasize, that teachers must acquire these competencies themselves to be able to teach them to their students, e.g., Redecker and Punie (2017), UNICEF’s ‘Educators’ Digital Competence Framework’ (2022), UNESCO ICT Competency Framework for Teachers (2011). However, despite teachers’ decisive role in students’ success with respect to digital competencies (European Commission, 2019), this aspect has to date received insufficient attention in teacher education. This is corroborated by the findings of a survey conducted by the Organisation for Economic Co-operation and Development (OECD), according to which 39% of teachers in the European Union (EU) admitted that they felt inadequately prepared for the everyday use of digital technologies in the classroom (European Commission, 2020a), compared to an OECD average of 43% (OECD, 2019). Significantly, teachers’ professional knowledge regarding information and communication technology (ICT) integration in the classroom is not only valuable in extreme situations, such as during the recent COVID-19 pandemic, e.g., to enable flexibility in action (König et al., 2020); rather, a professional knowledge base of this nature will also help teachers successfully implement innovations in the classroom (Mwendwa, 2017; König et al., 2022a).

Various initiatives at the national and international levels have established the goal of better preparing teachers for such challenges and providing them with more effective support. In Germany, the Federal Ministry of Education and Research (BMBF) has addressed the problem with various projects affiliated with the ‘Qualitätsoffensive Lehrerbildung’ ([Quality Initiative for Initial Teacher Education] BMBF, 2018). With the ‘Digital Education Action Plan’ (2021–2027), the EU is focusing explicitly on improving teachers’ digital competencies and skills, which is referred to as ‘Priority 2’ in the corresponding paper (European Commission, 2020b). In addition, in 2021, the UNESCO Institute for Information Technologies in Education (UNESCO IITE), Southeast Asian Ministers of Education Organization (SEAMEO), and the Teacher Task Force (TTF) led the first virtual ‘High-Level Forum on Teacher Competencies in the Digital Revolution: Reaching the Unreached’. One output of this forum was an ‘Action Agenda on Improving Teacher Competencies in the Digital Revolution’ (UNESCO IITE et al., 2021).

To address these requirements efficiently and effectively, evidence-based insights into preservice teachers’ professional knowledge as a learning outcome of initial teacher education and the opportunities to learn (OTL) to which they are exposed during their university education are required (Flores, 2020). A frequently cited approach in this regard is Mishra and Koehler’s (2006) technological pedagogical content knowledge (TPACK) model, according to which teachers' professional knowledge comprises general pedagogical knowledge (GPK), technological knowledge (TK), content knowledge (CK) and the resulting intersections. A cross-subject perspective on teachers' professional digital knowledge highlights the following knowledge components, which form the TPACK model – often illustrated by the much-reproduced Venn diagram (Mishra & Koehler, 2006, p. 1025): pedagogical knowledge (PK or GPK) on one side, TK on the other, and technological pedagogical knowledge (TPK) at their intersection (Fig. 1).

Recent years have witnessed much educational research dedicated to teachers' professional knowledge. For example, several studies have investigated GPK in German contexts (cf. König et al., 2018; Voss et al., 2015) as well as in other countries worldwide (König, 2014; Leijen et al., 2022). Several such studies also described and analysed the OTL available to student teachers (cf., König et al., 2017; Watson et al., 2018; Terhart, 2019; Depping et al., 2021). Perhaps because the amount of technological OTL offered in teacher education is still very scarce (e.g., Gudmundsdottir and Hatlevik, 2018), TPK and TK have received considerably less attention. For example, Lachner et al. (2019) developed a knowledge test to assess TPK, which has already been implemented in several studies (e.g., König et al., 2020). However, the findings as to whether or to what extent the individual knowledge components can be recorded separately or how OTL may affect teachers' professional knowledge have primarily been obtained from self-reports (cf. Scherer et al., 2017). Gerhard et al. (2023) is an exception in this regard: they applied knowledge tests for GPK and TPK and investigated the influences of the associated learning opportunities. As such, their study constitutes the first step towards countering Lachner et al.'s (2019) assertion that 'the interplay of these t-dimensions (e.g., TPK) and their basic knowledge

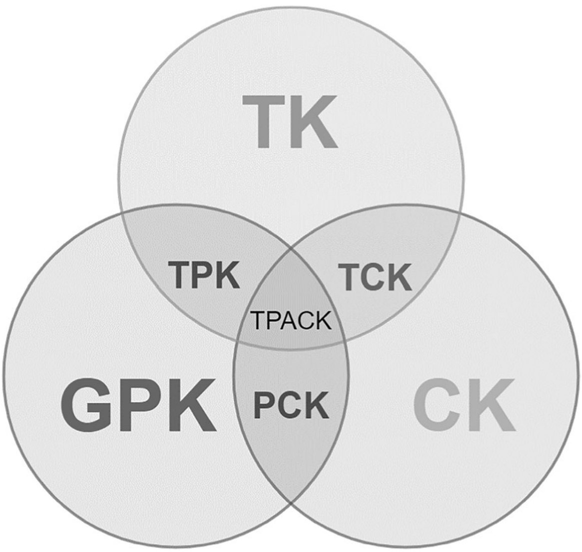

Fig. 1 The TPACK model

components (e.g., PK, TK) are less clear' (p. 9). However, knowledge in these areas is fundamental to digital literacy for educators (UNICEF, 2022). As recent developments in the field of artificial intelligence, exemplified by ChatGPT, have demonstrated, the education sector faces ever-evolving challenges in light of technological innovations (Zhu et al., 2023). Particularly, TK plays a crucial role in lifelong learning. The persistent evolution complicates the development of instruments that capture the requisite knowledge in its current necessary form (Mishra & Koehler, 2006). To the best of our knowledge, no knowledge test designed to measure TK and its associated OTL has been developed to date. Consequently, scientific knowledge regarding the interaction of GPK, TPK, and TK as well as how OTL may influence teachers' professional digital knowledge remains limited.

The present article addresses the corresponding research lacuna. We used data collected in 2022 as part of a central teacher education quality assurance initiative ('Bildungsmonitoring') implemented by the University of Cologne, which surveyed bachelor's and master's student teachers. The survey is part of a larger project entitled 'Zukunftsstrategie Lehrer*innenbildung Köln (ZuS): Heterogenität und Inklusion gestalten'. ZuS has been implemented in the 'Qualitätsoffensive Lehrerbildung' (Quality Initiative for Initial Teacher Education), a joint initiative of the Federal Government and the Länder that aims to improve the quality of teacher training. The programme is funded by the Federal Ministry of Education and Research [grant numbers 01JA1515, 01JA1815, and 01JA2003 (DiSK)]. In our study, we used three different test instruments to measure GPK, TPK, and TK. Preliminary analyses that focused exclusively on a bachelor's student sample and the simpler analysis of the bilateral relationship between GPK and TPK have already been published (Gerhard et al., 2023). In the present article, we offer new insights into the GPK–TPK–TK triad using a larger database of both bachelor's and master's student teachers. We thus build on the above-mentioned preliminary analyses (Gerhard et al., 2023) while extending the previously obtained insights by accounting for TK as another important component of teachers' knowledge for ICT integration in the classroom.

We choose these three knowledge components to provide an overview irrespective of specific teaching subjects, since indications of lacking technological OTL have been observed even at the generic level (Gerhard et al., 2023). Since digitalisation advances across all areas of society and is not limited to certain subject or content areas, schools and universities are required to take measures that will be applicable to teachers across all subjects and school types. Hence, associated knowledge is therefore of a fundamental nature and frequently independent of subject-specific requirements at first. Research indicates that the mere use of digital resources has not yet improved the teaching–learning process. Rather, the way in which they are used is crucial (Baker et al., 2018; Lei & Zhao, 2007) in terms of developing (preservice) teachers' competencies beyond their subject boundaries (Blikstad-Balas, 2023). As such, this paper focuses on the generic components of (preservice) teachers' professional digital knowledge, i.e., GPK, TPK, and TK.

Feasibility of conducting our research was another reason: To capture technological content knowledge (TCK), various subject-specific knowledge tests would need to be developed for the different teaching subjects and their academic disciplines. This was not feasible in our research project, and analysing the professional knowledge with TCK of various teaching subjects would inhibit research questions going far beyond the scope of the present article.

Moreover, comparing bachelor's and master's students regarding their knowledge allows for a more detailed examination of the knowledge acquisition within the three knowledge components. This analysis can yield insights into formal and informal OTL in these domains. With regard to the TPACK model, we anticipate achieving systemic comparability, as these students originate from the same institution before the divergence occurs during teacher training, and practical experience increase for in-service teachers.

2 State of research

2.1 Teachers' professional digital knowledge

The structure of preservice and in-service teachers' professional knowledge has changed in recent decades for reasons that include the new challenges that have arisen in the context of digitalisation (Koehler & Mishra, 2009; Mußmann et al., 2021). As early as 2006, Mishra and Koehler acknowledged these new challenges and added a technology component to the knowledge model developed by Shulman (1987). The resulting TPACK model includes a total of seven knowledge components (Mishra & Koehler, 2006): PK/GPK, CK, TPK, TK, technological content knowledge (TCK), pedagogical content knowledge (PCK), and TPACK.

We focus on GPK, TPK and TK because these are important competencies across subjects (see Sect. 3). The current status of research on this topic is outlined below.

2.1.1 General pedagogical knowledge (GPK)

Shulman (1987) identified GPK as one category of the knowledge base for teaching 'with special reference to those general principles and strategies of classroom management and organisation which seem to transcend the subject area' (p. 8). Various authors have demonstrated that GPK can be conceptually distinguished from other knowledge components, particularly those that pertain to specific subjects (Shulman, 1987; Baumert et al., 2010; König et al., 2022b). In a systematic literature review, König (2014) delineated three content areas of GPK: *instructional process*, *student learning*, and *assessment*. The area of *student learning* explicitly illustrates GPK's relevance for learners. Researchers broadly agree that GPK is a key determinant of teaching quality that affects students' learning growth and motivational development (König et al., 2021; Leijen et al., 2022).

2.1.2 Technological pedagogical knowledge (TPK)

The Venn diagram that visualises TPACK (Mishra & Koehler, 2006, p. 1025) illustrates TPK as resulting from the superposition of TK and GPK (Fig. 1). Shulman proposed the amalgam hypothesis, which suggested that PCK represents the correlation of the knowledge components PK and CK (Shulman, 1987). This hypothetical amalgam of PK and CK was later proven by Tröbst et al. (2018), among others. To the best of our knowledge, the extension of the amalgam hypothesis to the technological domain, i.e., PK, TK, and TPACK, has hitherto only been possible on the basis of self-reports. Luo et al. (2022), for example, have investigated the relationships between PK, TK, and TPK and their influence on TPACK. To demonstrate technology integration, they resort to items on self-efficacy, among others, and their results reveal significant correlations between the three knowledge components, i.e., PK, TK, and TPK (Luo et al., 2022). Existing definitions of TPK – such as that devised by Zhang et al. (2019), according to which TPK comprises 'knowledge about the use of new technologies to support general pedagogical activities' (p. 3443) – point in the same direction. This definition also clarifies TPK's distinction from TCK and TPACK, as TPK encompasses knowledge that is relevant to all subjects and is thus subject-independent (Guggemos & Seufert, 2021). However, this is not the sole reason that TPK is regarded as crucial for all teachers (Gerhard et al., 2023; Guggemos & Seufert, 2021): TPK is also considered an important requirement for teachers' ICT integration in the classroom (Gerhard et al., 2023; Lachner et al., 2019; Koehler & Mishra, 2009). Koh et al. (2013), for example, demonstrated that TPK – like TCK – not only exerts a positive influence on TPACK but that this influence is greater than that of TK and GPK. To capture the TPACK model's seven components, they used a survey developed by Chai et al. (2011). Koh et al.'s adapted survey comprised 30 items rated on a seven-point Likert scale measuring the degree of agreement or disagreement with statements about the seven different TPACK components.

2.1.3 Technological knowledge (TK)

Alongside GPK and CK, TK is one of the three basic components of the TPACK model (Mishra & Koehler, 2006) and 'refers to [(preservice)] teachers' knowledge and proficiency with technology tools' (Shinas et al., 2013, p. 341). In this context, Mishra and Koehler (2006) expressed criticism regarding the consideration of TK in isolation and instead advocate the integrated promotion of all technology components in professional and practical contexts. Guggemos and Seufert (2021) support this position, but Kaplon-Schilis and Lyublinskaya (2020) reported different findings. Using knowledge tests rather than self-reports in their study, they examined the basic components of the TPACK model with a subject focus on mathematics and science and tested their influence on TPACK without considering the intersections, i.e., TPK, TCK, and PCK. Although they used knowledge tests to capture TK, PK, and CK, TPACK was assessed using the TPACK Levels Rubric: 'The rubric was used to assess the teachers' written artifacts (lesson plans and authored curriculum materials) and observed behaviours (PD presentations and classroom teaching through observations)' (Lyublinskaya & Tournaki, 2012). Their findings reveal that their TPACK measure is independent from TK, PK, CKM, and CKS. Further analysis using multiple linear regression demonstrated that TK, PK, and CK are not significant predictors for their measure of TPACK. On this basis, they also refuted Koh et al.'s (2013) findings regarding TK's direct positive influence on TPACK (see the previous section for a description of the instrument used). Future studies should address the question of whether these studies' mixed findings may be attributable to the different approaches used to measure TPACK.

Despite the seemingly contradictory statements regarding the isolated consideration of TK, however, scholars agree that TK is important and necessary for preservice teachers (Guggemos & Seufert, 2021). The action-theoretical model *designing digital resources* highlights the importance of digital resources as an essential object of TK with respect to ICT integration in the classroom (Heine et al., 2022). In this context, it is precisely teachers' *knowledge about* such resources that aligns with TK (ibid.). Such knowledge encompasses, among other things, competent handling of CC licences or knowledge of copyright (cf., Redecker & Punie, 2017). TK is thus an integral part of teachers' knowledge base that facilitates their integration of ICT in the classroom. As such, it is important for all teachers, irrespective of the specific subjects that they teach.

2.2 Opportunities to learn (OTL)

In developing their professional (digital) knowledge during their initial teacher education, it is imperative that preservice teachers be provided with OTL (König et al., 2017; SWK, 2022). Moreover, student teachers' acquisition of professional knowledge can also be evaluated by how they respond to OTL (Blömeke et al., 2014; Floden, 2015). OTL include, among other things, the content with which student teachers have engaged up to a certain time point (Schmidt et al., 2011; König et al., 2017). Regarding the structure of academic OTL, 'the key components such as content of the subject […], the content of subject-specific didactics and the content of general pedagogy can be identified and empirically separated' (König et al., 2017). Accordingly, this structure also reflects the German university teacher training system and the associated knowledge components, whereby the educational sciences (GPK), subject sciences (CK), and subject didactics (PCK) are involved in prospective teachers' academic training.

While general pedagogical OTL has already been investigated and described extensively and its positive influence on preservice teachers' knowledge verified on several occasions (cf. König et al., 2017; Terhart, 2019; Depping et al., 2021), technological and technological pedagogical OTL remain relatively unexplored (Gerhard et al., 2023; Jäger-Biela et al., 2020). Wilson et al.'s (2020) meta-analysis of 38 studies goes some way toward addressing this desideratum, indicating an average positive effect of teacher education courses concerning technology integration on preservice teachers' knowledge ($d = 1.057$). However, it was not possible to determine conclusively which specific aspects of the courses contributed to the increase in knowledge (Wilson et al., 2020). König et al. (2022b) identified two intervention studies (pre–post design) in a scoping review that examined the effectiveness of OTL in improving preservice teachers' planning skills: both Neumann et al. (2021) and Zimmermann et al. (2021) reported significant increases in practice-relevant skills. The new approaches to teaching and learning that were required during the COVID-19 pandemic also demonstrated the importance of digital knowledge and its associated skills. König et al. (2020) found that students teachers' exposure to (digital-related) OTL during their university education positively influenced their ability to cope with the demands that the COVID-19 pandemic imposed on teachers. By contrast, Gerhard et al. (2023) observed no direct effect of technological pedagogical OTL on TPK. However, it was also evident that student teachers had not had significant exposure to OTL, mainly because they were surveyed as early as in their sixth semester of their bachelor's programmes – at least two years before graduating from university, after passing their Master of Education programme, which requires a further four semesters of study. This confirmed that OTL, which are instrumental in developing (preservice) teachers' professional digital knowledge, are not sufficiently anchored in the curricula for all student teachers (Bertelsmann Stiftung 2021; Jäger-Biela et al., 2020).

3 Research questions and hypotheses

This article is guided by two major research questions. First, we examine the structure of preservice teachers' professional knowledge required for ICT integration in the classroom across subjects. Second, we analyse the relationship between these knowledge facets and OTLs during teacher education. Considering the current state of the research (outlined above), we address the two research questions (RQ) with the following hypotheses (H):

> RQ1:What structure exists between the three knowledge components of GPK, TPK, and TK among student teachers?

We hypothesise that the above three components of preservice teachers' professional knowledge can be empirically separated (H1). The reasons for this assumption are, on the one hand, the existing fragmentation in teacher education. Hitherto, preservice teachers have acquired their professional knowledge through lectures and coursework pertaining to their subjects, subject didactics, and general pedagogy (see Sect. 4.1.4). Although the curricular structure relates to CK, PCK, and GPK, these knowledge components remain distinct, as few OTL explicitly target their linkage (König et al., 2017). We also expect this separation for the 'new' technological components, as they have not yet been integrated across all areas. On the other hand, we are also following Gerhard et al.s' (2023) findings that few OTL specific to these knowledge areas have been offered to date. We assume that this circumstance has led to technological OTL being added to rather than merged with the existing curriculum (Scheiter, 2021). On this basis, we hypothesise that the different knowledge components can be recorded separately. In line with Mishra and Koehler's (2006) model, we schematically favour the right-hand representation – which depicts professional knowledge in a three-dimensional model – over the left-hand model (Fig. 2), which considers professional knowledge as an overall factor without individual, separable components.

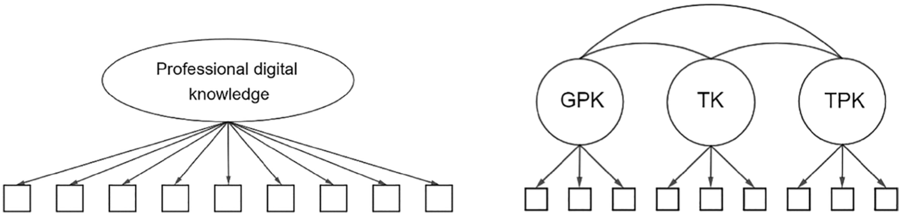

Fig. 2 Modelling teachers' professional knowledge as one-dimensional (left) and three-dimensional (right)

RQ2: Do preservice teachers' knowledge levels differ in relation to their exposure to OTL?

Regarding the preservice teachers' knowledge, we assumed that the master's students at the end of their first academic year would outperform the bachelor's students at the end of their first academic year in all three knowledge tests (H2a). Those enrolled in the master's programme had studied for three years more than those enrolled on the bachelor's programme, and thus the master's students had been exposed to significantly more OTL, allowing them to acquire more sophisticated professional knowledge with respect to facts, principles, and concepts and to enhance their existing knowledge. The modular structure of the teacher training programme at the University of Cologne ensures that some OTL are only offered in more advanced semesters. Thus, for example, all areas of competence are only fully covered upon completion of the degree. Simultaneously, this structure facilitates cumulative learning, as the offered content (partly) builds on that studied at earlier stages of the programme. Therefore, we assume that increasingly in-depth OTL will be offered to master's students in relation to all components of their professional knowledge (GPK, TPK, and TK). This will also have an impact on the level of knowledge in the three tests (H2b).

4 Method

4.1 Sampling design

The data for this study were collected as part of a central teacher education quality assurance initiative at the University of Cologne (cf. König et al., 2018). The University of Cologne is among the largest teacher education universities in Germany and the EU. The data collection period took place during the summer term in 2022. Both bachelor's and master's students at the end of their second semester were surveyed, providing two distinct groups for possible comparisons with respect to competence levels. Whereas the bachelor's students were in their first academic year at university, the master's students had completed their three-year bachelor's programme and had almost finished the first half of their master's programme (the Master of Education programme comprises two years in total). Interpretations of possible differences in

Table 1 Sample characteristics

	Bachelor						Master					
	Population		Sample		Included for analyses		Population		Sample		Included for analyses	
n	1249		386		320		737		316		299	
Teaching programme type	*N*	%	*n*	%	*n*	%	*N*	%	*n*	%	*n*	%
Primary Schools	154	12.3	58	15.0	53	16.6	104	14.1	49	15.5	45	15.1
Lower Secondary Schools, Intermediate Secondary Schools, and Comprehensive Schools	226	18.1	67	17.4	55	17.2	109	14.8	43	13.6	38	12.7
Grammar Schools and Comprehensive Schools	421	33.7	114	29.5	88	27.5	232	31.5	104	32.9	99	33.1
Vocational Colleges	61	4.9	20	5.2	12	3.8	59	8.0	24	7.6	23	7.7
Special Needs Education	387	31.0	127	32.9	112	35.0	233	31.6	96	30.4	94	31.4
	%		%		%		%		%		%	
Gender (female)	74,7		80.1		81.3		77,6		78.5		78.9	
			M	*SD*	*M*	*SD*			*M*	*SD*	*M*	*SD*
Age			21.3	3.4	21.2	3.3			25.9	3.8	25.9	3.9
GPA			2.1	.6	2.0	.6			2.2	.6	2.2	.6

Information on mean age and GPA of the population was not available knowledge (RQ 1) and OTL (RQ2) between the bachelor's and master's students thus relate to the three-year difference in study between the two groups (Table 1). All students in the target group were contacted via their internal university email address and invited to participate in the survey online ($N=1249$ bachelor's and $N=737$ master's students). Each student was offered a small financial incentive (10 euros) to complete the survey.

A total of $n=702$ students participated: $n=386$ bachelor's and $n=316$ master's students (response rate: 30.9% bachelor's; 42.9% master's; see Table 1).

For improved comparability of the test results, we considered only those students who had completed all three knowledge tests in our later analyses: a total of 619 students (320 bachelor's, 299 master's students; dropout: $n=83$). Considering the sample 'included for analyses' relative to the population, we observed a slight overrepresentation of preservice primary school and special needs education teachers compared to the bachelor's study population with differences of 4.3% and 4.0% respectively, while preservice grammar school and comprehensive school teachers were slightly underrepresented in the bachelor's sample. Here, the difference was 6.2%. In terms of gender, our sample for the analyses shows an overrepresentation for the female students in the bachelor's programme compared to the population with a difference of 6.6% (Table 1). Examination by χ^2-tests shows that these deviations are statistically significant (Teaching programme type: χ^2 ($n=320$; $df=4$) $=11.04$, $p=0.03$; Gender: χ^2 ($n=320$; $df=1$) $=7.38$, $p<0.01$). This does not apply to the differences between our master's sample and the population. Information on mean age and GPA of the population was not available.

4.2 Test instruments

4.2.1 Professional knowledge

To assess student teachers' GPK in this study, we used the test instrument developed for the *Teacher Education and Development Study – Mathematics* (TEDS-M; Blömeke et al., 2010; König & Blömeke, 2010). The three content areas already described in Sect. 4 are represented in the test by four subcategories: structure, adaptivity, assessment, and classroom management/motivation. The test consists of 42 items in total (see Table 2 for examples). Various earlier studies that used the survey instrument had already demonstrated its construct and curriculum validity (König, 2014; König et al., 2018; König et al., 2022b). Prognostic validity has also been demonstrated for instructional quality and student learning in secondary mathematics (König et al., 2021).

The TPK test, developed in 2020 by an interdisciplinary team of educational researchers and media psychologists (Gerhard et al., 2020; 2022; 2023), is based on six different content dimensions: classroom management, structuring, diagnosis, evaluation, motivating learners, and dealing with heterogeneity of learning groups. The TPK test combines this with the interdisciplinary, generic use of (digital) technologies (Gerhard et al., 2023). In total, the instrument includes 34 items (see Table 2 for examples).

Table 2 Item examples from the GPK, TPK, and TK tests

Knowledge area	Item example	Correct solution
GPK	Which of the following cases represents an example of intrinsic motivation, and which represents an example of extrinsic motivation? Check one box in each row (Response Categories: Intrinsic Motivation, Extrinsic Motivation) A student learns before a test in mathematics, because he/she… a) expects a reward for a good grade b) wants to avoid the consequences of a bad grade c) is interested in problems of mathematics d) does not want to disappoint his/her parents e) wants to maintain his/her relative rank in the class	Intrinsic motivation: c) Extrinsic motivation: a), b), d), e)
TPK	You give your students an extensive research task on the Internet over several weeks. The results are saved in the form of several image and text files and are then to be sent to you as an e-mail Which of the following files was saved by the group in a space-saving way? a) Research.zip b) Research.csv c) Research.rtf d) Research.pdf	a)
TK	Students are doing research for an assignment in class and click ‘agree’ directly when asked to accept cookies. You want students to think about this behaviour and give them hints. Which hint is wrong? a) By going to the settings in the pop-up window, you can select which cookies to allow with restrictions b) After installing a cookie dialog blocker on a computer, all cookies are automatically blocked c) Cookies can be managed through the browser d) There is a setting that decrees that cookies are automatically deleted after each session	b)

Our research group newly developed the TK test in 2021, with digital resources serving as the central reference based on findings from Heine et al.s' (2022) literature review. One key area of focus was the conceptual placement of digital resources in the TPACK model. The results revealed that knowledge about digital resources in particular can be assigned to the area of TK. Dealing with digital resources, meanwhile, lies in the transitional area between TK and TPK. Given that digital resources could be identified as a central topic of TK, we decided to include this as a focal point in the knowledge test as well. Moreover, the DigCompEdu also assigns them a high level of importance for preservice teachers through a separate competence area (Redecker & Punie, 2017). The test's design is intended to address several critiques. One of these pertains to the transfer of TK in isolation and addresses the significant fluctuation of this knowledge domain (Mishra & Koehler, 2006). To ensure that the test remained as stable as possible against such fluctuations over longer periods of time, the questions relate, among other things, to overarching aspects, such as the handling of licences, copyright, and data protection. These contents are also anchored, for example, in the *Medienkompetenzrahmen NRW* ([Media competence framework North Rhine-Westphalia], Medienberatung NRW, 2019). At the same time, it is necessary to embed the test items in authentic classroom contexts (Mishra & Koehler, 2006): although the test deals exclusively with TK content, this is situated in a pedagogical context. The aim is to provide examples of use from the school sector and thereby clearly demonstrate the relevance of this knowledge to preservice teachers (see Table 1 for examples).

The short test used in this study comprises 13 items. Based on the results of Heine et al.s' (2022) review, we distinguished between 'knowledge about' (7 items) and 'dealing with' (6 items) digital resources with respect to the cognitive demands. Nevertheless, care was taken to address pure TK despite the proximity to the intersections in the TPACK model – particularly TPK. As such, we expect that TPK and TK can be empirically separated (RQ1).

4.2.2 OTL

We used three different survey instruments to capture OTL. In all three, the students were asked to indicate whether, during their initial teacher education, they had already been exposed to specific content in general pedagogy, technological pedagogy, and technology. The response options were dichotomous ('yes' = 1 and 'no' = 0). A survey instrument developed by König et al. (2017) closely aligned with the subcategories of the GPK test was used to capture OTL relating to GPK. This 37-item instrument assesses the pedagogical OTL. The items are distributed over four subscales: structuring, adaptivity, assessment and classroom management/motivation (Table 3). The same applies to the instrument for surveying OTL regarding the TPK (Gerhard et al., 2022, 2023). Analogous to the structure of the TPK test, the OTL instrument consists of six different subscales and the 31 items are closely aligned with them. The subscales are classroom management, structuring, diagnosis, evaluation, motivating learners, and dealing with heterogeneity of learning groups (Table 3). We removed the evaluation subscale for analyses (Gerhard et al.,

Table 3 OTL items and reliability of the scales (Cronbach's Alpha)

Dimension	Scale	Number of items	Item example	Cronbach's Alpha
Pedagogical OTL				
Instructional Process	P-Structuring	9	Analysing own teaching	.86
	P-Adaptivity	11	Differentiated instruction	.83
Assessment	P-Assessment	9	Forms of teacher feedback	.88
Student Learning	P-Classroom Management/Motivation	8	Whole-class motivation	.85
Technological pedagogical OTL				
Instructional Process	TP-Classroom Management	8	Use of digital word processing programs (e.g., Word) by students	.83
	TP-Structuring	6	Cooperative learning in the classroom with etherpads	.77
Assessment	TP-Diagnosis	4	Use of digital learning platforms for the performance assessment of students	.76
Student Learning	TP-Motivating Learners	5	Student learning with adaptive learning software	.78
	TP-Dealing with Heterogeneity of learning groups	7	Use of assistive technologies with heterogeneous student body	.83
Technological OTL				
Digital Resources	T-Digital Resources	13	Technical application and use of gamification in teaching	.85

2022). The test to assess OTL in relation to TK consists of 13 items and also aligns with the TK test's structure. The scale refers to different forms and aspects of digital resources, as conceptualised by Heine et al. (2022).

4.3 Scaling and data analysis

To address our first research question (RQ1), we conducted a scaling in accordance with item response theory (IRT) using the *ConQuest* software package (Adams et al., 2020). Each test item is assigned an item parameter ('difficulty parameter') based on its empirical frequency ('solution rate'), and all individuals are assigned an 'ability parameter' based on their response behaviour using the maximum likelihood procedure.

ConQuest allows the generation of deviance statistics as well as the determination of the Akaike information criterion (AIC) and the Bayesian information criterion (BIC). To increase the analytical power of the scaling analysis, the maximum possible number of cases was included respectively in the modelling (Bond et al., 2020). The deviance statistic (i.e., –2*log likelihood) of the model was generated. The deviation index (*deviance*; Wu & Adams, 2006) compares the global fit of the models examined and provides information on which of the models best fits the data (*degree of goodness of fit*). A smaller deviation indicates a better fit. To assess the empirical reliability of the three test instruments, we applied the *expected* a posteriori estimation (EAP; De Ayala et al., 1995). This is comparable to Cronbach's alpha and permits an unbiased description of the population parameters (Wu et al., 1997). If the three-dimensional model were to fit the data better, the IRT test results from the three-dimensional modelling (EAP estimates derived from the *ConQuest* scaling analysis) would be used to present the descriptive statistics.

To test the statistical influence of OTL on knowledge in terms of correlations, we first combined the individual items of the OTL into subscales ('item parceling'; Bandalos & Finney, 2009). Next, we calculated several regression models with the software package *Mplus* (Muthén and Muthén, 1998-2017). The EAP scores of the three different knowledge tests were each considered as dependent variables.

Different regression models were calculated for each of the three knowledge tests. Model 1 may be considered the 'base model'. The study section serves as the independent variable. In Model 2, the effects of study section are determined using gender and grade point average (GPA) as control variables. Subsequent models also consider the effects of OTL. Given that the GPK-OTL are correlated with one another, not only the OTL but also the individual subscales are included in the calculation to avoid multicollinearity. The same applies to the TPK-OTL but not to the TK-OTL, since there is only one scale in total here.

5 Results

5.1 Findings on the structure of professional knowledge (RQ1)

To address our first research question (RQ1) concerning the structure of preservice teachers' professional knowledge, we calculated different structural models (see the schematic representation for the one- and three-dimensional models in Fig. 2). Table 4 illustrates the deviance for different dimensional models, including the calculated results for AIC and BIC. They are based on the deviance statistics and consider both the number of parameters and the sample size.

AIC and BIC are lower for the three-dimensional than the one-dimensional model. A significant improvement in model fit was indicated by the deviance statistics. To perform a more in-depth analysis, in addition to examining our hypothesised structure of having three-dimensions (H1), we additionally computed several two-dimensional models with GPK, TPK, or TK each being compared with the other two knowledge components subsumed to a second dimension, respectively. As the findings presented in Table 4 illustrate, none of these two-dimensional models fit the data better than the hypothesised three-dimensional model.

The results support the first hypothesis (H1) and favour the three-dimensional model over the one-dimensional model for preservice teachers' professional digital knowledge.

Furthermore, all weighted mean squares of the 89 items are within the recommended range for both the one-dimensional ($0.89 < \text{MNSQ} < 1.15$) and three-dimensional ($0.84 < \text{MNSQ} < 1.17$) models. The average item discrimination ranges from 0.26 to 0.28. Table 5 summarises the central statistical parameters from the IRT scaling analysis of the three-dimensional model.

Table 6 details the latent intercorrelations for the three surveyed knowledge components. While high intercorrelations are shown for TK and TPK (>0.8), those between GPK and TK or between GPK and TPK may be classified as moderately high (>0.5) following Cohen's (1992) recommendations.

ConQuest – the software used for IRT scaling – provides an item-person map. Figure 3 illustrates this for the three-dimensional model, with the student

Table 4 Deviance statistics of the different dimensions

Model	Deviance	Number of estimated parameters	Difference			AIC	BIC
			Deviance	Parameter	*p*		
1-dim	47418.26	90	191.02	5	<.001	47598.26	47996.79
2-dim (TK)	47371.55	92	144.31	3	<.001	47555.55	47962.94
2-dim (TPK)	47360.50	92	133.26	3	<.001	47544.50	47951.89
2-dim (GPK)	47247.86	92	20.62	3	<.001	47431.86	47839.25
3-dim	47227.24	95				47417.24	47837.91

The values in the column 'Difference—Deviance' result from the deviation from the three-dimensional model

Table 5 Statistical parameters from the IRT scaling analysis of the three-dimensional model

	Items	EAP/PV reliability	Theta-Variance	Weighted mean square (min.-max.)	Item-Discrimination (on average)
GPK	42	.750	.468	.84 – 1.17	.28
TPK	34	.721	.359	.91 – 1.14	.26
TK	13	.694	.559	.89 – 1.10	.28

teachers' ability shown on the left side. A single X represents 3.6 student teachers. The difficulty level of the test items is indicated on the right side. Each item has a number corresponding to the numbering in the scaling analysis (1–89). In the three-dimensional model, each item is assigned to a single dimension. Students whose ability parameter on that dimension is equal to the difficulty parameter for that item have a 50% chance of success on that item (Adams et al., 2022). Thus, the higher a person's ability parameter is on this scale, the more likely it is that they will successfully complete the task. The three test instruments cover the students' abilities satisfactorily. This may be deduced from the fact that the difficulty levels of the items (right) reflect the individual abilities (left) well. Furthermore, the three-dimensional model and its results demonstrate that it was possible to create a test score for each dimension of professional digital knowledge, i.e., GPK, TPK, and TK. The three instruments' EAP reliabilities are each within an acceptable range (Table 5). Given that the three-dimensional model fits better, we exported the EAP estimates from it. For further analyses and improved readability, the EAP estimates were linearly transformed to a mean of 50 and a standard deviation of 10 for each of the GPK, TPK, and TK scales (Table 7).

5.2 Findings on the relationship between knowledge and OTL (RQ 2)

The statistics outlined in Table 7 demonstrate that, according to our second hypothesis (H2), master's students significantly outperform bachelor's students in all three knowledge tests. Based on the transformed EAP estimates, we calculated a *t-test for independent samples*. Given that hypothesis testing always depends on sample size, we also computed effect size d (Cohen, 1992). While the effect for GPK can clearly be classified as strong, it is in the upper-middle range for TPK and TK (Cohen, 1992).

Table 6 Latent intercorrelations of student teachers' GPK, TPK, and TK

	GPK	TPK
GPK		
TPK	.64	
TK	.59	.84

```
                 Dimension                  Terms in the Model (excl Step terms)
---------------------------------------------
       Dimension_1  Dimension_2  Dimension_3                  +item
--------------------------------------------------------------------------------------
                   |            |            |7                                      |
                   |            |            |                                       |
                   |            |            |16                                     |
                   |            |            |                                       |
                   |            |            |                                       |
                   |            |            |                                       |
                   |            |            |                                       |
                   |            |            |                                       |
   2               |            |            |                                       |
                  X|            |            |                                       |
                  X|            |            |                                       |
                   |            |            |31 62 78                               |
                 XX|            |            |41                                     |
                  X|            |            |8                                      |
                XXX|            |           X|5 79                                   |
                 XX|            |           X|14 27                                  |
               XXXX|           X|         XXX|28 42                                  |
               XXXX|           X|         XXX|52 56 73 89                            |
   1        XXXXXXX|           X|        XXXX|9 32 63                                |
            XXXXXXX|         XXX|         XXX|                                       |
          XXXXXXXXX|         XXX|       XXXXX|60 61 70                               |
          XXXXXXXXX|         XXX|     XXXXXXX|39                                     |
         XXXXXXXXXX|       XXXXX|      XXXXXX|6 18 85                                |
         XXXXXXXXXX|      XXXXXX|    XXXXXXXX|76 84                                  |
        XXXXXXXXXXX|   XXXXXXXXX|    XXXXXXXX|55 69 77                               |
      XXXXXXXXXXXXX|   XXXXXXXXX|     XXXXXXX|15 29 53 72 74                         |
         XXXXXXXXXX|   XXXXXXXXX|   XXXXXXXXX|4 24 35 59                             |
          XXXXXXXXX|  XXXXXXXXXX|   XXXXXXXXX|3 71 88                                |
   0       XXXXXXXX|XXXXXXXXXXXX|  XXXXXXXXXX|51 66 86                               |
            XXXXXXX| XXXXXXXXXXX|    XXXXXXXX|40 47 57 65                            |
           XXXXXXXX|XXXXXXXXXXXX|    XXXXXXXX|19 49                                  |
              XXXXX|XXXXXXXXXXXX|   XXXXXXXXX|46 50 58 80                            |
             XXXXXX|  XXXXXXXXXX|  XXXXXXXXXX|26                                     |
            XXXXXXX| XXXXXXXXXXX|      XXXXXX|44 64                                  |
               XXXX|    XXXXXXXX|      XXXXXX|1 2 23                                 |
                 XX|      XXXXXX|      XXXXXX|38 54 68 75                            |
                XXX|      XXXXXX|     XXXXXXX|13 30                                  |
               XXXX|       XXXXX|       XXXXX|21 81 83                               |
  -1             XX|       XXXXX|        XXXX|10 17 37                               |
                 XX|         XXX|        XXXX|                                       |
                  X|         XXX|        XXXX|20                                     |
                  X|          XX|          XX|11 22 33 45                            |
                  X|           X|           X|67                                     |
                  X|           X|          XX|                                       |
                   |           X|            |48                                     |
                  X|           X|           X|                                       |
                   |            |           X|12 36 87                               |
                   |            |           X|43                                     |
  -2               |            |           X|82                                     |
                   |            |            |34                                     |
                   |            |            |                                       |
                   |            |            |                                       |
                   |            |            |                                       |
                   |            |            |25                                     |
                   |            |            |                                       |
                   |            |            |                                       |
                   |            |            |                                       |
                   |            |            |                                       |
  -3               |            |            |                                       |
======================================================================================
Each 'X' represents 3.6 cases
```

Fig. 3 Item–person map of three-dimensional Rasch scaling

Table 8 details the descriptive statistics of the OTL subscales. Comparison of the mean values of the individual scales between bachelor's and master's student teachers reveals a difference for all subscales, indicating that master's students had

Table 7 Testing for test score differences among bachelor and master student teachers

	Bachelor ($n=320$)			Master ($n=299$)			t	df	p	Effect size Cohen's d
	M	SD	SE	M	SD	SE				
GPK	49.89	5.84	.33	55.09	4.72	.27	– 12.21	604.79	< .001	.98
TPK	46.21	5.01	.28	49.96	4.42	.26	– 9.83	617	< .001	.79
TK	47.08	6.08	.34	51.24	5.66	.33	– 8.78	617	< .001	.71

Because of variance heterogeneity in the *t*-test for GPK, the corrected *df* value is reported here ($df=604.79$)

Table 8 Descriptive statistics for the OTL scales

OTL Category	Subscale	Bachelor			Master			
		M	SE	SD	M	SE	SD	η^2
Pedagogical OTL								
Instructional Process	P-Structuring	.31	.01	.25	.79	.01	.20	.53
	P-Adaptivity	.26	.01	.23	.59	.01	.25	.32
Assessment	P-Assessment	.31	.02	.32	.67	.02	.30	.24
Student Learning	P-Classroom Management/Motivation	.29	.02	.29	.62	.02	.31	.23
Technological pedagogical OTL								
Instructional Process	TP-Classroom management	.20	.02	.28	.32	.02	.30	.04
	TP-Structuring	.15	.01	.24	.32	.02	.29	.09
Assessment	TP-Diagnosis	.13	.01	.25	.28	.02	.34	.07
Student Learning	TP-Motivating Learners	.13	.01	.24	.33	.02	.33	.11
	TP-Dealing with Heterogeneity of learning groups	.11	.01	.22	.24	.02	.29	.06
Technological OTL								
Digital Resources	T-Digital Resources	.10	.01	.18	.15	.01	.21	.02

been exposed to more OTL than bachelor's students. The effect of the differences evaluated by η^2 in the last column varies considerably. By far the largest effect can be seen in the difference of the subscale 'P-Structuring' in the area of pedagogical OTL. While the difference in means is absolutely 0.48, the effect size may be classified as large, with $\eta^2=0.53$. The other pedagogical OTL subscales also reveal a significant difference between the two groups of students with a mean of approximately 0.30. By contrast, the difference for OTL with a technological component is small. Although medium effects are still shown for the subscales of technological pedagogical OTL (Cohen, 1992), the average difference in absolute terms is small (0.15). For the pure technological OTL, the difference is of no practical significance.

For the technological knowledge components, OTL scarcely appears to play any part in teacher education: even in the master's programme, only 30% of the students on average indicated that they had been exposed to the content in their studies hitherto. For the pure technological content, the value for master's students is even lower at 15%.

To assess the possible influences of the different OTLs on students' performance in the knowledge tests, the intercorrelations of study variables were calculated using *Mplus* (latent) and *SPSS* (manifest) (Table 12 in the Appendix).

In the subsequent regression analyses, the relationships between OTL and knowledge persist for the various dependent variables, even after controlling for gender and GPA. The negative GPA correlations are due to the German scoring scheme, wherein a 1 represents the best score and a 4 represents the worst score.

Table 9 summarises the results of the regression analyses with the GPK test score as the dependent variable. In addition to the influences of the different subscales, we also determined the influence of the overall score for the OTL in the GPK domain (GPK-OTL). With the exception of the 'P-OTL Assessment' subscale, the other OTL for GPK show highly significant statistical influences on students' GPK knowledge test scores (Table 10).

The regression analyses with TPK knowledge test score as the dependent variable indicate that OTL in the TPK domain has a small, insignificant negative impact on test scores, as demonstrated by the overall score TP-OTL score (−0.050). In the case of the subscale 'TP-OTL Dealing with Heterogeneity of learning groups', this is of minor significance. Only the subscale 'TP-OTL Structuring' shows slightly positive influence.

The regression analyses with the EAP score of the TK knowledge test reveal results similar to those for the TPK (Table 11). However, the influence of TK-OTL may be evaluated as stable with −0.001.

Table 9 Findings from regression analyses with GPK test score as dependent variable

Predictors	M1 β	M2 β	M3 β	M4 β	M5 β	M6 β	M7 B
Bachelor vs Master	.439***	.459***	.304***	.335***	.443***	.402***	.187**
Control variables							
Gender		.020	.037	.006	.015	.022	−.006
GPA		−.173***	−.193***	−.190***	−.174***	−.188***	−.192***
GPK-OTL							
P-OTL ST			.246***				
P-OTL AD				.242***			
P-OTL AS					.046		
P-OTL CM						.147**	
GPK-OTL							.359***
R^2	.192***	.222***	.176***	.200***	.210***	.201***	.273***

Bachelor vs Master (BA = 0; MA = 1), Gender (0 = female; 1 = male), GPA ➔ great point average (Abiturnote), P-OTL ST ➔ P-OTL Structuring, P-OTL AD ➔ P-OTL Adaptivity, P-OTL AS ➔ P-OTL Assessment, P-OTL CM ➔ P-OTL Classroom Management/Motivation; GPK-OTL ➔ overall score for GPK-OTL; *p < .05; **p < .01; ***p < .001

Table 10 Findings from regression analyses with TPK test score as dependent variable

Predictors	M1 β	M2 β	M3 β	M4 β	M5 β	M6 β	M7 β	M8 β
Bachelor vs Master	.368***	.395***	.399***	.389***	.405***	.395***	.409***	.411***
Control variables								
Gender		.031	.040	.035	.045	.037	.046	.039
GPA		−.232***	−.231***	−.239***	−.231***	−.237***	−.230***	−.227***
TPK-OTL								
TP-OTL CM			−.047					
TP-OTL ST				.014				
TP-OTL DI					−.056			
TP-OTL MO						−.012		
TP-OTL HE							−.080*	
TP-OTL								−.050
R^2	.135***	.189***	.193***	.186***	.198***	.189**	.205***	.191***

Bachelor vs Master (BA = 0; MA = 1), Gender (0 = female; 1 = male), GPA ➔ great point average (Abiturnote), TP-OTL CM ➔ TP-OTL Classroom Management, TP-OTL ST ➔ TP-OTL Structuring, TP-OTL DI ➔ TP-OTL Diagnosis, TP-OTL MO ➔ TP-OTL Motivating learners, TP-OTL HE ➔ TP-OTL Dealing with Heterogeneity of learning groups, TP-OTL ➔ overall score for TP-OTL; *$p < .05$; **$p < .01$; ***$p < .001$

Table 11 Findings from regression analyses with TK test score as dependent variable

Predictors	M 1 β	M 2 β	M 3 β
Bachelor vs Master	.333***	.360***	.356***
Control variables			
Gender		.046	.053
GPA		−.233***	−.239***
TK-OTL			
TK-OTL			−.001
R^2	.111***	.165***	.223***

Bachelor vs Master (BA = 0; MA = 1), Gender (0 = female; 1 = male), GPA ➔ great point average (Abiturnote), TK_OTL ➔ overall score for TK-OTL; *$p < .05$; **$p < .01$; ***$p < .001$

6 Discussion

Herein, we have aimed to clarify the structure of teachers' professional knowledge (RQ1). Building on conceptual work by Shulman (1987) and Mishra and Koehler (2006) regarding teacher knowledge components, we argued that the professional knowledge required for teachers' integration of ICT in the classroom across subjects is multidimensional in nature. According to our hypothesis (H1), generalised knowledge is insufficient to cope with the diverse and increasingly complex demands of digitalisation in education (Mußmann et al., 2021). Rather, teachers require individual knowledge components, such as GPK, TPK, and TK. Our second hypothesis (H2a), which assumed a higher level of knowledge across all three knowledge components among master's students compared to bachelor's students, was supported. However, our findings confirmed the expected link only for the relationship between general pedagogical OTL and GPK. The detailed insight that initial teacher education programmes offer into curricular content and the level of knowledge that student teachers exhibit not could be confirmed for either TPK or TK. Therefore, we could not fully confirm H2b.

6.1 Structure of professional knowledge

Three standardised knowledge tests were used to address the question regarding the structure of preservice teachers' professional knowledge required to meet the challenges associated with integrating ICT into classroom teaching across subjects (RQ1). The findings from the IRT scaling analysis reveal that the three-dimensional model is a significantly better fit for the data than the one-dimensional model. While the three-dimensional model distinguishes between GPK, TPK, and TK, the one-dimensional model operationalises knowledge across all test items.

The correlation between the knowledge tests with the technical components (TPK and TK) is higher than that shown by both with GPK. However, the correlation between TPK and GPK is slightly higher than that between TK and GPK. Nonetheless, the fact that they are discrete constructs was also verified by the three different two-dimensional models of the IRT scaling analyses. The three-dimensional model is also superior to the three models (Table 4). However, the three knowledge components are not inter-correlated in the same way. One possible reason for the tests' stronger correlation with the technological components may be that the TK items were embedded in educational contexts to raise the preservice teachers' awareness of the technical aspects' relevance for school and teaching (Sect. 6.2.1). At the same time, it may be more difficult to delineate TK and TPK from one another. Nonetheless, empirical findings highlight the importance of distinguishing between TK and TPK.

6.2 Different levels of professional knowledge

In addressing RQ2, we investigated whether differences in student teachers' knowledge in relation to their OTL could be discerned. Our analyses revealed that preservice teachers attain different levels of knowledge depending on their initial teacher education career stage.

However, superior performance can only be attributed to the students' OTL to a limited extent (H2b). The regression analyses showed that GPK-OTL in particular exert a positive statistically significant influence on student knowledge. Contrary to our expectations, the influence of OTL with a technological component is negligible, if not non-existent. This may be attributed to several possible factors.

Our survey found that student teachers are exposed to very few TK-OTL and TPK-OTL. Thus, the demonstrably low correlation between technological OTL and students' TK and TPK may be due to a lack of provision at the institutional level (Gerhard et al., 2023). The relatively limited provision of technological OTL may also be due to its curricular status as not yet conventional, as is the case for GPK-OTL in Germany (Terhart, 2019). Teacher education is progressing slowly in terms of integrating offerings that involve a technological component (Gudmundsdottir & Hatlevik, 2018). Based on our survey of students from the University of Cologne, we can corroborate Bertelsmann's (2021) assertion that the incorporation of mandatory courses on digital media literacy into the curriculum showed only minimal progress between 2017 and 2020. Our findings extend this observation into 2022.

Although we were unable to find a direct link between the content aspects of technological pedagogical or technological OTL and corresponding preservice teacher TPK and TK, it is promising that both knowledge components nevertheless appear to play a significant role in initial teacher education. Given that the master's students outperformed the bachelor's students, we assume that specific OTL supports the acquisition not only of conventional GPK but also of such innovative knowledge facets as TPK and TK. This is also evident in the comparison of students based on their chosen school type.

As the present study is one of the first to apply standardised tests rather than self-reports, the mean differences in TPK and TK between bachelor's and master's students, with middle effect size, emerge as an important component amid the various research desiderata relating to digitalisation in educational contexts. However, future research should continue to investigate which OTL are most salient with respect to fostering such components of the teacher professional knowledge base.

6.3 Pedagogical implications

The results of our analyses generally illustrate that the classification of knowledge components as proposed by Mishra and Koehler (2006) is useful.

Teachers' professional knowledge must be viewed as a multidimensional construct. While we might consider this to be an argument in favour of no longer taking a critical view of the isolated promotion of TK (Guggemos & Seufert, 2021; Mishra & Koehler, 2006), we still should not definitively reject interdisciplinary promotion. The COVID-19 pandemic, among other phenomena, has highlighted that teachers' ability to be flexible in their thoughts and actions is a competence that transcends disciplines and knowledge (König et al., 2020). TK, in particular, can enhance this flexibility for the current era of digitalisation (Heine et al., 2022).

To support preservice teachers in developing their digital competencies, the promotion of all three knowledge components, i.e., GPK, TPK, and TK, should be accounted for during teacher education programmes and early career teacher induction. The recent rapid spread of ChatGPT has highlighted the significance of teacher education and teacher professional development institutions responding promptly and effectively to technological innovations. Instead of prohibiting these innovations at the university level (The Guardian, 2023), OTL need to be established that fit the rapidly emerging challenges. These avenues should facilitate the development and enhancement of preservice teachers' competencies, in particular related to TK, in utilizing such innovations effectively. Additionally, for preservice teachers, specific OTL approaches must be implemented, enabling them to impart these competencies to their future students, which demands an appropriate acquisition of TPK. Thus, the demands that international educational institutions place on preservice teachers' digital competencies may be met (UNESCO, 2011; UNICEF, 2022; Redecker & Punie, 2017).

6.4 Limitations and future research

Although the study was conducted at only a single university in Germany, we are confident that the findings from our analyses for RQ1 are relevant both nationally and internationally. As noted in the introduction, various national and international institutions have made it their goal to prepare teachers for the demands of digitalisation. This undertaking is particularly relevant to teacher education institutions, e.g., Redecker and Punie (2017). The widespread use of the TPACK model at the international level also indicates that this is a topic of global interest.

This study explicitly refers to the entire professional knowledge of (preservice) teachers. In the TPACK model, different knowledge areas are addressed, of which we have examined the three cross-disciplinary ones (GPK, TPK and TK). Nevertheless, the exclusion of subject-specific knowledge components represents a limitation. As such, future investigations focusing on specific subjects and involving the various subject didactics and disciplines are warranted. For instance, the DiKoLeP project (*Digital Competencies of Pre-Service Physics Teachers*; Große-Heilmann et al., 2022) has devised a university teaching approach to enhance the digital-media PCK among preservice physics teachers. Future research could aim to combine cross-disciplinary and subject-specific domains to comprehensively address the entire TPACK model.

The cohort comparison, i.e., the comparison between bachelor's and master's study sections, is based on a simple cross-sectional analysis. Generalised conclusions derived from study section on the level of knowledge are therefore limited in their validity. However, we compared the two samples on the basis of several socio-demographic characteristics and consequently, the samples are comparable samples (see the Methods section). Nevertheless, it would be interesting for future studies to examine the individual developmental progression of the students on a longitudinal study plan. It is possible that students benefit from early learning opportunities and can then make better use of further learning opportunities later in their studies.

The test instrument used to measure TK comprises 13 items only. Therefore, the findings potentially limited generalizability cannot be overlooked. An extended test version, consisting of 25 items, that was not available for the present study, will be applied in future investigations.

As the findings reveal, few OTL are provided in the area of TK. The concrete influence that these exert on students' performance and knowledge levels can thus be assessed only to a limited extent. For this reason, a learning module was developed within the context of a seminar. In accordance with intervention study guidelines, the OTL and knowledge will be surveyed and analysed again.

Moreover, the query regarding OTL was conducted through student self-report, and comparison with the university curriculum with respect to the technological components of OTL was only made for TPK (Gerhard et al., 2023; Jäger-Biela et al., 2020). However, the students' self-reports suggest that digitalisation has yet to fully assert itself in the teacher education curriculum, at least at the University of Cologne. To fully appreciate the reasons for the differences between the bachelor's and master's students, further investigation will be necessary. Informal OTL may play a role, but these were not surveyed in the present study.

7 Conclusion

In this study, 619 teacher education students from the University of Cologne participated. Among them, 320 were in their second bachelor's semester, and 299 were in their second master's semester. Through the use of three distinct knowledge tests assessing GPK, TPK, and TK, it was empirically demonstrated that these knowledge components can be distinguished from each other.

The evidence supporting this conclusion was derived from an IRT-Rasch scaling analysis, which indicated that the three-dimensional model outperformed the one-dimensional model. Additionally, master's students outperformed bachelor's students in all three knowledge components. However, when analysing OTL, only the regression analysis for GPK reveals that general pedagogical OTL had a statistically significant impact on the difference in knowledge levels between bachelor's and master's students. Technological OTL provision for preservice teachers was lacking.

This raises the question of whether the limited availability of technological OTL or the effectiveness of existing curricular provision accounts for this finding. Further investigation in future research is warranted to delve into this matter.

Appendix

Table 12 manifest and latent Intercorrelations of the study variables

	Bachelor vs. Master	GPA	Gender	P-OTL ST	P-OTL AD	P-OTL AS	P-OTL CM	TK-OTL	TP-OTL CM	TP-OTL ST	TP-OTL DI	TP-OTL MO	TP-OTL HE	TPK	TK	GPK
Bachelor vs. Master	1	.125**	.055	.726**	.561**	.494**	.473**	.131	.191**	.304**	.258**	.330**	.246**	.368**	.333**	.439**
GPA	.125	1	.056	.144**	.108**	.058	.130**	.025	.148**	.098*	.172**	.094*	.116**	-.181**	-.185**	-.114**
Gender	.058	.056	1	.115**	.094*	.105**	.013	.169**	.096*	.155**	.163**	.110**	.116**	.053	.061	.037
P-OTL ST	.726***	.144***	.117**	1	.723**	.530**	.568**	.217**	.320**	.401**	.354**	.400**	.334**	.353**	.330**	.420**
P-OTL AD	.561***	.108**	.092*	.723***	1	.504**	.629**	.221**	.310**	.389**	.338**	.377**	.334**	.327**	.301**	.410**
P-OTL AS	.494***	.058	.124**	.529***	.504***	1	.376**	.204**	.245**	.312**	.307**	.318**	.283**	.214**	.194**	.254**
P-OTL CM	.473***	.130**	.019	.568***	.629***	.376***	1	.286**	.378**	.412**	.374**	.421**	.410**	.236**	.212**	.306**
TK-OTL	.131**	.024	.168***	.216***	.220***	.203***	.285***	1	.507**	.525**	.434**	.491**	.519**	.059	.049	.067
TP-OTL CM	.188***	.147***	.094*	.317***	.308***	.244***	.377***	.507***	1	.685**	.635**	.617**	.619**	-.001	-.031	.073
TP-OTL ST	.303***	.096*	.158***	.400***	.388***	.311***	.411***	.525***	.684***	1	.668**	.630**	.604**	.115**	.083*	.159**
TP-OTL DI	.257***	.167***	.170***	.353***	.337***	.307***	.373***	.435***	.635***	.668***	1	.647**	.679**	.017	-.014	.081*

Table 12 (continued)

	Bachelor vs. Master	GPA	Gender	P-OTL ST	P-OTL AD	P-OTL AS	P-OTL CM	TK-OTL	TP-OTL CM	TP-OTL ST	TP-OTL DI	TP-OTL MO	TP-OTL HE	TPK	TK	GPK
TP-OTL MO	.327***	.092*	.113**	.399***	.375***	.317***	.418***	.489***	.616***	.630***	.647***	1	.717**	.101*	.069	.138**
TP-OTL HE	.244***	.114**	.129**	.331***	.332***	.282***	.409***	.519***	.619***	.603***	.679***	.717***	1	.000	-.029	.049
TPK	.368***	-.181***	.042	.353***	.327***	.214***	.236***	.059	-.003	.114**	.019	.099*	-.001	1	.959**	.782**
TK	.333***	-.185***	.055	.330***	.301***	.194***	.212***	.048	-.032	.083*	-.014	.067	-.031	.959***	1	.743**
GPK	.439***	-.114**	.039	.420***	.410***	.254***	.306***	.067	.072	.159***	.079*	.137**	.048	.782***	.743***	1

latent correlations under diagonal, manifest correlations above diagonal; GPA ➔ great point average (Abiturnote), P-OTL ST ➔ P-OTL Structuring, P-OTL AD ➔ P-OTL Adaptivity, P-OTL AS ➔ P-OTL Assessment, P-OTL CM ➔ P-OTL Classroom Management/Motivation, TP-OTL CM ➔ TP-OTL Classroom Management, TP-OTL ST ➔ TP-OTL Structuring, TP-OTL DI ➔ TP-OTL Diagnosis, TP-OTL MO ➔ TP-OTL Motivating learners, TP-OTL HE ➔ TP-OTL Dealing with Heterogeneity of learning groups; $^{*}p<.05$; $^{**}p<.01$, $^{***}p<.001$

Funding Open Access funding enabled and organized by Projekt DEAL. The research reported in this article was supported by the Federal Ministry of Education and Research of Germany (BMBF) under grant numbers 01JA1515, 01JA1815, and 01JA2003 (DiSK). The projects “Digitalstrategie Lehrer*innenbildung Köln” (DiSK) and “Zukunftsstrategie Lehrer*innenbildung” (ZuS) are part of the “Qualitätsoffensive Lehrerbildung”, a joint initiative of the Federal Government and the Länder, which aims to improve the quality of teacher training.

The programme is funded by the Federal Ministry of Education and Research. The authors are responsible for the content of this publication.

Data availability The datasets used for analyses in this paper are not available.

Declarations

Disclosure statement No potential conflict of interest was reported by the authors.

References

Adams, R. J., Wu, M. L., Cloney, D., Berezner, A., & Wilson, M. (2020). *ACER ConQuest: Generalised Item Response Modelling Software* (Version 5.29) [Computer software]. Australian Council for Educational Research. https://www.acer.org/au/conquest

Adams, R., Cloney, D., Wu, M., Osses, A., Schwantner, V., & Vista, A. (2022). *ACER Conquest Manual*. https://conquestmanual.acer.org/conquestManual.pdf. Accessed 25 Sept 2023

Baker, J. P., Goodboy, A. K., Bowman, N. D., & Wright, A. A. (2018). Does teaching with PowerPoint increase students’ learning? A meta-analysis. *Computers & Education, 126*, 376–387. https://doi.org/10.1016/j.compedu.2018.08.003

Bandalos, D. L., & Finney, S. J. (2009). Item parceling issues in structural equation modeling. In G. A. Marcoulides & R. E. Schumacker (Eds.), *New developments and techniques in structural equation modeling* (pp. 269–296). Lawrence Erlbaum.

Baumert, J., Kunter, M., Blum, W., Brunner, M., Voss, T., Jordan, A., Klusmann, U., Krauss, S., Neubrand, M., & Tsai, Y.-M. (2010). Teachers’ Mathematical Knowledge, Cognitive Activation in the Classroom, and Student Progress. *American Educational Research Journal, 47*(1), 133–180. https://doi.org/10.3102/0002831209345157

Bertelsmann Stiftung. (2021). *Lehrkräfte vom ersten Semester an für die digitale Welt qualifizieren. Policy Brief November 2021*. Retrieved from https://2020.monitor-lehrerbildung.de/export/sites/default/.content/Downloads/Monitor-Lehrerbildung_Digitale-Welt_Policy-Brief-2021.pdf. Access March 30, 2023

Blikstad-Balas, M. (2023). ICT in the Classroom – Didactical Challenges for Practitioners and Researchers. In F. Ligozat, K. Klette, & J. Almqvist, *Didactics in a Changing World. European Perspectives on Teaching, Learning and the Curriculum. Transdisciplinary Perspectives in Educational Research*, vol 6 (217–235). Springer, Cham. https://doi.org/10.1007/978-3-031-20810-2_13. Accessed 25 Sept 2023

Blömeke, S., Kaiser, G., & Lehmann, R. (2010). *TEDS-M 2008 - Professionelle Kompetenz und Lerngelegenheiten angehender Sekundarstufenehrkräfte im internationalen Vergleich*. Münster: Waxmann.

Blömeke, S., Hsieh, F. J., Kaiser, G., & Schmidt, W. (2014). *International perspectives on teacher knowledge, beliefs and opportunities to learn. Advances in Mathematics Education*. Springer, Dordrecht. https://doi.org/10.1007/978-94-007-6437-8_20. Accessed 25 Sept 2023

Bond, T., Yan, Z., & Heene, M. (2020). Applying the Rasch Model: Fundamental Measurement in the Human Sciences (4th ed.). Routledge. https://doi.org/10.4324/9780429030499. Accessed 25 Sept 2023

Bundesministerium für Bildung und Forschung (BMBF). (2018). *Richtlinie zur Förderung von Projekten in der „Qualitätsoffensive Lehrerbildung" mit den Schwerpunkten „Digitalisierung in der Lehrerbildung" und/oder „Lehrerbildung für die beruflichen Schulen"*, Bundesanzeiger vom 19.11.2018. Bonn: BMBF.

Chai, C. S., Koh, J. H. L., Tsai, C. C., & Tan, L. W. L. (2011). Modeling primary school pre-service teachers' technological pedagogical content knowledge (TPACK) for meaningful learning with information and communication technology (ICT). *Computers & Education, 57*(1), 1184–1193. https://doi.org/10.1016/j.compedu.2011.01.007

Cohen, J. (1992). Statistical power analysis. *Current Directions in Psychological Science, 1*(3), 98–101. https://doi.org/10.1111/1467-8721.ep10768783

De Ayala, R. J., Schafer, W. D., & Sava-Bolesta, M. (1995). An investigation of the standard errors of expected a posteriori ability estimates. *British Journal of Mathematical and Statistical Psychology, 48*(2), 385–405. https://doi.org/10.1111/j.2044-8317.1995.tb01070.x

Depping, D., Ehmke, T., & Besser, M. (2021). Aus "Erfahrung" wird man selbstwirksam, motiviert und klug: Wie hängen unterschiedliche Komponenten professioneller Kompetenz von Lehramtsstudierenden mit der Nutzung von Lerngelegenheiten zusammen? *Zeitschrift Für Erziehungswissenschaft, 24*(1), 185–211. https://doi.org/10.1007/s11618-021-00994-w

European Commission, Directorate-General for Education, Youth, Sport and Culture. (2019). *Key competences for lifelong learning*, Publications Office. https://data.europa.eu/doi/https://doi.org/10.2766/569540

European Commission. (2020a). *Digital Education Action Plan 2021–2027. Resetting education and training for the digital age*. Retrieved from https://education.ec.europa.eu/sites/default/files/document-library-docs/deap-factsheet-sept2020a_en.pdf. Accessed March 30, 2023

European Commission. (2020b). *Communication from the Commission to the European Parliament, The Council, The European Economic and Social Committee and the Committee of the Regions Digital Education Action Plan 2021–2027: Resetting education and training for the digital age*.

Floden, R. (2015). Learning what research says about teacher preparation. In M. J. Feuer, A. I. Berman, & R. C. Atkinson (Eds.), *Past as prologue: the National Academy of Education at 50 Members Reflect* (pp. 279–284). Washington, DC: National Academy of Education.

Flores, M. A. (2020). Preparing teachers to teach in complex settings: Opportunities for professional learning and development. *European Journal of Teacher Education, 43*(3), 297–300. https://doi.org/10.1080/02619768.2020.1771895

Gerhard, K., Kaspar, K., Rüth, M., Kramer, C., Jäger-Biela, D., & König, J. (2020). Entwicklung eines Testinstruments zur Erfassung technologisch-pädagogischen Wissens von Lehrpersonen. In K. Kaspar, M. Becker-Mrotzek, S. Hofhues, J. König, & D. Schmeinck (Eds.), *Bildung, Schule, Digitalisierung* (pp. 365–370). Münster: Waxmann.

Gerhard, K., Kaspar, K., Rüth, M., Jäger-Biela, D., & König, J. (2022). *Technologisch-pädagogisches Wissen (TPK) und Technologisch-pädagogische Ausbildungsinhalte (TP OTL):Dokumentation der Instrumente für die Kompetenzmessung und Erfassung von Lerngelegenheiten bei (angehenden) Lehrkräften.*

Gerhard, K., Jäger-Biela, D., & König, J. (2023). Opportunities to learn, technological pedagogical knowledge, and personal factors of pre-service teachers: Understanding the link between teacher education program characteristics and student teacher learning outcomes in times of digitalization. *Zeitschrift für Erziehungswissenschaft, 26*(3).

Große-Heilmann, R., Riese, J., Burde, J. P., Schubatzky, T., & Weiler, D. (2022). Fostering pre-service physics teachers' pedagogical content knowledge regarding digital media. *Education Sciences, 12*(7), 440. https://doi.org/10.3390/educsci12070440

Gudmundsdottir, G. B., & Hatlevik, O. E. (2018). Newly qualified teachers' professional digital competence: Implications for teacher education. *European Journal of Teacher Education, 41*(2), 214–231. https://doi.org/10.1080/02619768.2017.1416085

Guggemos, J., & Seufert, S. (2021). Teaching with and teaching about technology–Evidence for professional development of in-service teachers. *Computers in Human Behavior, 115*, 1–11. https://doi.org/10.1016/j.chb.2020.106613

Heine, S., Krepf, M., & König, J. (2022). Digital resources as an aspect of teacher professional digital competence: One term, different definitions–a systematic review. *Education and Information Technologies, 1–28*,. https://doi.org/10.1007/s10639-022-11321-z

Jäger-Biela, D., Kaspar, K., & König, J. (2020). Lerngelegenheiten zum Erwerb von digitalisierungsbezogenen Medienkompetenzen. In K. Kaspar, M. Becker-Mrotzek, S. Hofhues, J. König, & D. Schmeinck (Eds.), *Bildung, Schule, Digitalisierung* (pp. 66–72). Münster: Waxmann.

Kaplon-Schilis, A., & Lyublinskaya, I. (2020). Analysis of relationship between five domains of TPACK framework: TK, PK, CK math, CK science, and TPACK of pre-service special education teachers. *Technology, Knowledge and Learning, 25*(1), 25–43. https://doi.org/10.1007/s10758-019-09404-x

Koh, J. H. L., Chai, C. S., & Tsai, C. C. (2013). Examining practicing teachers' perceptions of technological pedagogical content knowledge (TPACK) pathways: A structural equation modeling approach. *Instructional Science, 41*(4), 793–809. https://doi.org/10.1007/s11251-012-9249-y

König, J. (2014). *Designing an international instrument to assess teachers' General Pedagogical Knowledge (GPK): Review of studies, considerations, and recommendations*. Technical paper prepared for the OECD Innovative Teaching for Effective Learning (ITEL)-Phase II Project: A Survey to Profile the Pedagogical Knowledge in the Teaching Profession (ITEL Teacher Knowledge Survey). OECD.

König, J., & Blömeke, S. (2010). *Pädagogisches Unterrichtswissen (PUW). Dokumentation der Kurzfassung des TEDS-M-Testinstruments zur Kompetenzmessung in der ersten Phase der Lehrerausbildung*. Humboldt-Universität.

König, J., Doll, J., Buchholtz, N., Förster, S., Kaspar, K., Rühl, A.-M., Strauß, S., Bremerich-Vos, A., Fladung, I., & Kaiser, G. (2018). Pädagogisches Wissen versus fachdidaktisches Wissen? Struktur des professionellen Wissens bei angehenden Deutsch-, Englisch- und Mathematiklehrkräften im Studium. *Zeitschrift für Erziehungswissenschaft, 21*(3), 1–38. https://doi.org/10.1007/s11618-017-0765-z

Koehler, M. J., & Mishra, P. (2009). What Is Technological Pedagogical Content Knowledge? *Contemporary Issues in Technology and Teacher Education, 9*(1), 60–70.

König, J., Borowski, A., Lindmeier, A., & Zlatkin-Troitschanskaia, O. (2022a). Transfer of digitalized teaching-learning and assessment tools in higher education – approaches and best practices [Themenheft]. *Zeitschrift für Erziehungswissenschaft.*

König, J., Hanke, P., Glutsch, N., Jäger-Biela, D., Pohl, T., Becker-Mrotzek, M., Schabmann, A., & Waschewski, T. (2022b). Teachers' professional knowledge for teaching early literacy: Conceptualization, measurement, and validation. *Educational Assessment, Evaluation and Accountability, 34*, 483–507. https://doi.org/10.1007/s11092-022-09393-z

König, J., Ligtvoet, R., Klemenz, S., & Rothland, M. (2017). Effects of opportunities to learn in teacher preparation on future teachers' general pedagogical knowledge: Analyzing program characteristics and outcomes. *Studies in Educational Evaluation, 53*, 122–133. https://doi.org/10.1016/j.stueduc.2017.03.001

König, J., Jäger-Biela, D., & Glutsch, N. (2020). Adapting to online teaching during COVID-19 school closure: Teacher education and teacher competence effects among early career teachers in Germany. *European Journal of Teacher Education, 43*(4), 608–622. https://doi.org/10.1080/02619768.2020.1809650

König, J., Blömeke, S., Jentsch, A., Schlesinger, L., Felske, C., Musekamp, F., & Kaiser, G. (2021). The links between pedagogical competence, instructional quality, and mathematics achievement in the lower secondary classroom. *Educational Studies in Mathematics, 107*, 189–212. https://doi.org/10.1007/s10649-020-10021-0

Lachner, A., Backfisch, I., & Stürmer, K. (2019). A test-based approach of modeling and measuring technological pedagogical knowledge. *Computers & Education, 142*, 1–13. https://doi.org/10.1016/j.compedu.2019.103645

Lei, J., & Zhao, Y. (2007). Technology uses and student achievement: A longitudinal study. *Computers & Education, 49*(2), 284–296. https://doi.org/10.1016/j.compedu.2005.06.013

Leijen, Ä., Malva, L., Pedaste, M., & Mikser, R. (2022). What constitutes teachers' general pedagogical knowledge and how it can be assessed: A literature review. *Teachers and Teaching, 28*(2), 206–225. https://doi.org/10.1080/13540602.2022.2062710

Luo, W., Berson, I. R., Berson, M. J. & Park. (2022). An Exploration of Early Childhood Teachers' Technology, Pedagogy, and Content Knowledge (TPACK) in Mainland China. *Early Education and Development*, 1–16. https://doi.org/10.1080/10409289.2022.2079887

Lyublinskaya, I., & Tournaki, N. (2012). The Effects of Teacher Content Authoring on TPACK and on Student Achievement in Algebra. In R. N. Ronau, C. R. Rakes, & M. L. Niess, M. L. *Teacher Knowledge, and Classroom Impact: A Research Handbook on Frameworks and Approaches* (295–322). IGI Global.

Medienberatung NRW (2019). *Broschüre Medienkompetenzrahmen NRW [Leaflet media competence framework North-Rhine Westphalia]*. Münster: Medienberatung NRW.

Mishra, P., & Koehler, M. J. (2006). Technological Pedagogical Content Knowledge: A Framework for Teacher Knowledge. *Teachers College Record, 108*(6), 1017–1054. https://doi.org/10.1111/j.1467-9620.2006.00684.x

Mußmann, F., Hardwig, T., Riethmüller, M., & Klötzer, S. (2021). *Digitalisierung im Schulsystem 2021: Arbeitszeit, Arbeitsbedingungen, Rahmenbedingungen und Perspektiven von Lehrkräften in Deutschland. Ergebnisbericht*. https://doi.org/10.3249/ugoe-publ-10

Muthén, L.K., & Muthén, B.O. (1998–2017*). Mplus user's guide: Statistical analysis with latent variables* (7th ed.). Los Angeles, CA: Muthén & Muthén.

Mwendwa, N. K. (2017). Perception of teachers and principals on ICT integration in the primary school curriculum in Kitui County. *Kenya. European Journal of Education Studies, 3*(7), 408–430. https://doi.org/10.5281/zenodo.824829

Neumann, K. L., Alvarado-Albertorio, F., & Ramirez-Salgado, A. (2021). Aligning with Practice: Examining the Effects of a practice-based Educational Technology Course on Preservice Teachers' Potential to Teach with Technology. *TechTrends, 65*(6), 1027–1040. https://doi.org/10.1007/s11528-021-00672-y

Organisation for Economic Co-operation and Development (OECD). (2019). TALIS 2018 Results (Volume I): *Teachers and School Leaders as Lifelong Learners*. *TALIS, OECD Publishing, Paris.* https://doi.org/10.1787/1d0bc92a-en

Redecker, C., & Punie, Y. (2017). *European Framework for the Digital Competence of Educators: DigCompEdu*. European Commission, Joint Research Centre, Punie, Y. (ed), Publications Office. https://doi.org/10.2760/159770

Scheiter, K. (2021). Lernen und Lehren mit digitalen Medien: Eine Standortbestimmung. *Zeitschrift Für Erziehungswissenschaft, 24*(5), 1039–1060. https://doi.org/10.1007/s11618-021-01047-y

Scherer, R., Tondeur, J., & Siddiq, F. (2017). On the quest for validity: Testing the factor structure and measurement invariance of the technology-dimensions in the Technological, Pedagogical, and Content Knowledge (TPACK) model. *Computers & Education, 112*, 1–17. https://doi.org/10.1016/j.compedu.2017.04.012

Schmidt, W. H., Cogan, L., & Houang, R. (2011). The role of opportunity to learn in teacher preparation: An international context. *Journal of Teacher Education, 62*(2), 138–153. https://doi.org/10.1177/0022487110391987

Shinas, V. H., Yilmaz-Ozden, S., Mouza, C., Karchmer-Klein, R., & Glutting, J. J. (2013). Examining domains of technological pedagogical content knowledge using factor analysis. *Journal of Research on Technology in Education, 45*(4), 339–360. https://doi.org/10.1080/15391523.2013.10782609

Shulman, L. S. (1987). Knowledge and Teaching: Foundations of the New Reform. *Harvard Educational Review, 57*(1), 1–23. https://doi.org/10.17763/haer.57.1.j463w79r56455411

SWK [Ständige Wissenschaftliche Kommission der Kultusministerkonferenz]. (2022). Digitalisierung im Bildungssystem: Handlungsempfehlungen von der Kita bis zur Hochschule. Gutachten der Ständigen Wissenschaftlichen Kommission der Kultusministerkonferenz (SWK). https://doi.org/10.25656/01:25273

Terhart, E. (2019). Teacher education in Germany. *In Oxford Research Encyclopedia of Education*. https://doi.org/10.1093/acrefore/9780190264093.013.377

The Guardian. (2023). New York City schools ban AI chatbot ChatGPT. The Guardian. Retrieved from https://www.theguardian.com/us-news/2023/jan/06/new-york-city-schools-ban-ai-chatbot-chatgpt. Accessed August 4, 2023

Tröbst, S., Kleickmann, T., Heinze, A., Bernholt, A., Rink, R., & Kunter, M. (2018). Teacher knowledge experiment: Testing mechanisms underlying the formation of preservice elementary school teachers' pedagogical content knowledge concerning fractions and fractional arithmetic. *Journal of Educational Psychology, 110*(8), 1049–1065. https://doi.org/10.1037/edu0000260

UNESCO IITE, SEAMEO & TTF. (2021). *Teacher Competencies in the Digital Revolution: Reaching the Unreached*. Retrieved from https://iite.unesco.org/news/teacher-competencies-in-the-digital-revolution/. Accessed March 30, 2023

UNICEF. (2022). *Educators' Digital Competence Framework*. Retrieved from https://www.unicef.org/eca/media/24526/file/Educators'%20Digital%20Competence%20Framework.pdf. Accessed March 30, 2023

United Nations Educational, Scientific and Cultural Organization. (2011). UNESCO ICT Competency Framework for Teachers. UNESCO, Paris. Retrieved from https://unesdoc.unesco.org/ark:/48223/pf0000213475. Accessed July 28, 2023

Voss, T., Kunina-Habenicht, O., Hoehne, V., & Kunter, M. (2015). Stichwort Pädagogisches Wissen von Lehrkräften: Empirische Zugänge und Befunde. *Zeitschrift Für Erziehungswissenschaft, 18*(2), 187–223. https://doi.org/10.1007/s11618-015-0626-6

Watson, C., Seifert, A., & Schaper, N. (2018). Die Nutzung institutioneller Lerngelegenheiten und die Entwicklung bildungswissenschaftlichen Wissens angehender Lehrkräfte. *Zeitschrift Für Erziehungswissenschaft, 21*(3), 565–588. https://doi.org/10.1007/s11618-017-0794-7

Wilson, M.L., Ritzhaupt, A.D., & Cheng, L. (2020). The impact of teacher education courses for technology integration on pre-service teacher knowledge: A meta-analysis study. *Computers and Education, 156*. https://doi.org/10.1016/j.compedu.2020.103941

Wu, M. L., & Adams, R. J. (2006). Modeling mathematics problem solving item response using a multidimensional IRT model. *Mathematics Education Research Journal, 18*, 93–113. https://doi.org/10.1007/bf03217438

Wu, M., Adams, R. J., & Wilson, M. (1997). Multilevel item response models: An approach to errors in variables regression. *Journal of Educational and Behavioral Statistics, 22*(1), 47–76. https://doi.org/10.2307/1165238

Zhang, S., Liu, Q., & Cai, Z. (2019). Exploring primary school teachers' technological pedagogical content knowledge (TPACK) in online collaborative discourse: An epistemic network analysis. *British Journal of Educational Technology, 50*(6), 3437–3455. https://doi.org/10.1111/bjet.12751

Zhu, C., Sun, M., Luo, J., Li, T., & Wang, M. (2023). How to harness the potential of ChatGPT in education. *Knowledge Management & E-Learning, 15*(2), 133–152. https://doi.org/10.34105/j.kmel.2023.15.008

Zimmermann, F., Melle, I., & Huwer, J. (2021). Developing Prospective Chemistry Teachers' TPACK – A Comparison between Students of Two Different University and Expertise Levels regarding Their TPACK self-efficacy, Attitude, and Lesson Planning Competence. *Journal of Chemical Education, 98*(6), 1863–1874. https://doi.org/10.1021/acs.jchemed.0c01296

Authors and Affiliations

Sandra Heine[1] · **Matthias Krepf**[1] · **Daniela J. Jäger-Biela**[1] · **Kristina Gerhard**[1] · **Rebecca Stollenwerk**[1] · **Johannes König**[1]

✉ Sandra Heine
s.heine@uni-koeln.de

Matthias Krepf
matthias.krepf@uni-koeln.de

Daniela J. Jäger-Biela
daniela.julia.jaeger-biela@iais.fraunhofer.de

Kristina Gerhard
kristina.gerhard@uni-koeln.de

Rebecca Stollenwerk
rebecca.beys@uni-koeln.de

Johannes König
johannes.koenig@uni-koeln.de

[1] Empirical School Research, University of Cologne, Gronewaldstr. 2, 50931 Cologne, Germany