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Fostering Knowledge Facets of the TPACK Framework Through Designing Digital Mathematical Escape Games – A Qualitative Content Analysis of Pre-Service Teachers' Self-Reported Learnings and Challenges

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Abstract
To prepare pre-service teachers for the multiple requirements of their future math teaching within the digital age, they need to develop all facets of knowledge mentioned in the Technological Pedagogical Content Knowledge (TPACK) framework to enhance their digital competences. Research has shown that teachers learn to use technology by designing educational technologies for authentic use while activating and extending their knowledge regarding the interplay of technology, pedagogy, and content. In this study, 58 pre-service primary and secondary teachers from three German universities created and evaluated their own digital mathematical escape games (DIMEG) within a seminar. Since it has scarcely been researched how the design process of DIMEG addresses pre-service teachers' technological, pedagogical and content knowledge, this study aims to investigate their subjectively reported learnings and challenges. For this, an online-based questionnaire with four open-ended items on their learnings and five open-ended items on the encountered challenges during the design process allowed them to reflect on their knowledge and skill development. All 471 answers were categorized by applying qualitative content analysis. Results indicate most learnings in the pre-service teachers' pedagogical content knowledge (PCK), technological knowledge (TK), and technological pedagogical content knowledge (TPCK). Regarding the challenges that appeared during the process of creating a DIMEG, pre-service teachers reported struggling most with the development of mathematical problems, their adaption to students' heterogeneity, and their meaningful integration into the storyline of the game. Based on this study, we claim that designing DIMEG provide a powerful context to address and intertwine relevant facets of knowledge for pre-service math teachers.

Keywords Escape games · Game development-based learning · Teacher education · Professional development

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Introduction

The 21st century, as the digital age, requires (prospective) teachers to develop digital competences. According to the European Commission's definition, *digital competence* "[…] involves the confident, critical and responsible use of, and engagement with, digital technologies for learning, at work, and for participation in society" (European Commission: Directorate-General for Education, Youth, Sport and Culture [EU Commission], 2019, p. 10). It encompasses knowledge (e.g., concepts), skills (e.g., the ability to carry out processes), and attitudes (e.g., a mindset to act) (Vuorikari et al., 2022). To support the acquisition of digital competence, teacher education should provide knowledge for teaching with technology and skills for the use of technologies. This study focuses on both through the lens of Technological Pedagogical Content Knowledge (TPACK) framework (Mishra & Koehler, 2006) which describes the interplay of content, pedagogy, and technology (see Zhang & Tang, 2021 for an overview). Effective concepts such as learning-by-design (Mishra & Koehler, 2006) and integrated approach (Mouza et al., 2014) have successfully fostered TPACK facets by engaging pre-service teachers (PST) in lesson or tool design, its implementation, and reflection (Mishra & Koehler, 2006; Mouza et al., 2014).

This study examines the digital game development in teacher education to address all TPACK facets while fostering digital skills. Digital games are recognized increasingly as valuable for both student learning and PST education. Using games already requires diverse technological knowledge (TK) and skills, attitudes and experiences of teachers (Meletiou-Mavrotheris & Prodromou, 2016), while designing them demands profound knowledge and skills which many in-service teachers currently lack (Romero & Proulx, 2018; Takeuchi & Vaala, 2014; Vu & Gaskill, 2018). However, integrating pedagogical knowledge (PK) and mathematical content knowledge (CK) with general and game-specific TK equips teachers to select, evaluate, and productively utilize digital games instructionally (Meletiou-Mavrotheris & Prodromou, 2016).

Designing educational games has emerged as powerful learning and teaching approach for teacher learning (Mishra & Koehler, 2006; Wu & Wang, 2012). A notable subgenre is the escape game (EG), which integrates authentic problems into an immersive narrative under time constraints (Nicholson, 2015; Van Eck, 2015). EG research indicates promising results for education from primary school to professional development (Fotaris & Mastoras, 2019; Makri et al., 2021). Both playing and designing EG promote diverse competencies (e.g., 21st-century skills) and development of TPACK among PST (Piñero Charlo et al., 2021; Şahin, 2023; Weisberg et al., 2022). Yet, these studies either focus on interdisciplinary or other subjects than mathematics, or they examine the development of analog or hybrid EG. Thus, it has not been explored whether or how the development of digital mathematical escape games (DIMEG) fosters the acquisition of facets within TPACK among PST.

Thus, this study aims to specify the potential of DIMEG within university education for PST. It builds on a seminar where PST developed and implemented their own DIMEG. Data were collected via an online questionnaire and qualitatively analyzed to explore the self-reported learnings and challenges of PST regarding the TPACK facets of knowledge after designing a DIMEG.

Background

TPACK Framework

The TPACK framework is widely used to conceptualize and analyze the multi-faceted teacher knowledge. It evolved from studies focusing on "how" teachers learn to teach with technologies (Koehler & Mishra, 2005; Mishra & Koehler, 2003, 2006), expanding Shulman's (1986, 1987) pedagogical content knowledge (PCK) by incorporating the knowledge of technologies (Mishra & Koehler, 2006). They argue that focusing solely on specific tools or media is insufficient, given the fast-paced evolution of technology (Mishra & Koehler, 2003). Instead, TPACK emphasizes the balanced consideration of content, pedagogy, and technology, resulting in the integrated knowledge facet known as technological pedagogical content knowledge (TPCK) (Mishra & Koehler, 2006).

This study adopts a transformative (Angeli & Valanides, 2009; Graham, 2011) rather than an integrative perspective on TPACK framework, viewing the intersectional facets TPCK, TPK, and TCK (Table 1) not as simple overlaps but as distinct knowledge facets that require explicit instruction to develop (Schmid et al., 2020).

Table 1 Knowledge facets in the TPACK framework (Mishra & Koehler, 2006)

Knowledge facet	Description of the knowledge facet
content knowledge (CK)	knowledge about content specific concepts
pedagogical knowledge (PK)	subject independent knowledge of practices and methods of teaching and learning
pedagogical content knowledge (PCK)	subject specific knowledge about content specific teaching strategies and methods, targeted knowledge and concepts students need to have around the subject matter; knowledge about students' obstacles within the learning process of a specific content
technological knowledge (TK)	knowledge about (digital) technologies and skills to operate them
technological content knowledge (TCK)	knowledge of the influence of different technologies on the representation of content
technological pedagogical knowledge (TPK)	knowledge about the features of technologies that influence general teaching and learning processes
technological pedagogical content knowledge (TPCK)	knowledge about the most appropriate teaching strategies and methods that include supportive technologies to learn about a content; knowledge about potentials of technologies concerning students' ways of the subject matter acquisition

TPCK, in this view, transforms rather than simply combines CK, PK, and TK, forming a new type of professional knowledge (Schmid et al., 2020). Mishra and Koehler (2006) define seven interrelated knowledge facets which serve as an analytical tool for this study (see Table 1).

To foster TPACK development, various approaches and models have been developed, including lesson study, microteaching, and the learning-by-design approach (Zhang & Tang, 2021). Rooted in the "learning by doing" (Mishra & Koehler, 2003), learning-by-design engages PST in collaboratively design and implementation processes tailored to specific content and student needs (Mishra & Koehler, 2003, 2006; Mouza et al., 2014; Zhang & Tang, 2021). The design process itself, rather than theoretical instruction, effectively activates and extends PSTs' knowledge facets (Koehler et al., 2007; Mishra & Koehler, 2006). However, PST may need structured scaffolding due to limited classroom experience (Zhang & Tang, 2021). Accordingly, this study integrates the learning-by-design approach into a structured seminar where PST develop and implement DIMEG.

Playing Digital Games for Learning

Playing games have long been integrated into (mathematics) education as a motivating and rich medium for learning, and especially the digital share of games has increased significantly since technology has advanced rapidly. Also, research began to focus on the potentials, challenges, and changes of digital games involved in (mathematics) education and especially examined serious games. Serious games "involve pedagogy [in the] activities that educate or instruct, thereby imparting knowledge or skill" (Zyda, 2005, p. 26). A subcategory of serious games includes educational games which are specifically designed to support teaching and learning processes in education (Horvat et al., 2022; Van Eck, 2015). Nevertheless, educational games include the same aspects as serious games to capture the players and engage them cognitively: entertainment elements, game flow, and story (Devlin, 2011; Zyda, 2005). Since players do not read a manual before they are immersed in the game, they explore, try, fail, and succeed by developing strategies, resorting to hidden clues, and immediately giving feedback (Devlin, 2011). Digital games designed for learning therefore include a "constructivist component" that requires students to construct new knowledge and, build on their previous knowledge base to experience the game (Vu et al., 2014).

Escape Games in Mathematics Education

A genre of educational games is the escape game (EG), and particularly escape rooms. In these games, the players have to escape from a room or an unpleasant situation or have to rescue someone from a predicament by discovering clues and accomplishing tasks collaboratively in teams within a limited amount of time (Nicholson, 2015; Stohlmann, 2023; Tusche et al., 2023). A prominent feature of digital games, and especially EG, is the authentic integration of problem-solving tasks (Van Eck, 2015). It is a prerequisite for constantly activating the players cognitively and keeping them motivated (Devlin, 2011). Their immersion in the game respectively, their perceived game flow, is determined by the setting, the story, and the meaningfully embedded tasks, and problems (Botturi & Babazadeh, 2020; Vidergor, 2021). When integrated into a (realistic) story with an achievable but challenging aim, the player is asked to be creative and make use of all given hints, his or her previous knowledge, strategies, and skills to solve the problems (Stohlmann, 2023). The players furthermore develop and discuss their ideas with each other and receive immediate feedback from the game after making decisions. In other words – and pointed out by several studies – EG are intrinsically motivating and engaging, enhance autonomy, engage students cognitively, and can foster important skills of the 21st century (e.g., creativity and problem-solving) (Fotaris & Mastoras, 2019; Fuentes-Cabrera et al., 2020; Jiménez et al., 2020; Pg Abu Bakar et al., 2023; Saleh Alabdulaziz, 2023; Vidergor, 2021). Besides these general potentials for learning, (digital) EG are also an appropriate medium for supporting and improving the acquisition of specific mathematical competences and knowledge among students of all ability levels (Andrews & Bagdasar, 2023; Pg Abu Bakar et al., 2023) and for reducing mathematics learning anxiety (Fuentes-Cabrera et al., 2020; Saleh Alabdulaziz, 2023). Thus, (digital) mathematical EG are a promising way of teaching mathematics that are of increasing interest in research.

For an insight into a DIMEG, we illustrate parts of 'Zottel: the circus goat' as an example for primary school. In the story, students prepare a school circus performance (Fig. 1, left) by rehearsing tricks with Zottel, the circus goat. Yet, just before the performance, Zottel disappeared. Apparently, she had discovered the principal's secret stock of sugar in his safe and accidentally locked herself in. It is the players aim, to search for clues and complete a series of problem-based tasks to eventually discover the code of the safe and free Zottel (Fig. 1, right).

An EG always follows a story embedded in a specific context. These games are usually divided into (three) episodes (introduction, task episode, conclusion) with different purposes. The introduction allows players the immersion in the game and the story. Typically, this is the episode to present the goal of the game (Werther, 2019), which often implies to escape from a challenging situation (Nicholson, 2015; Vidergor, 2021) and to mention the given time. The story continues by solving various (problem-solving) tasks. A rather typical problem-solving task in the DIMEG 'Zottel' is illustrated in Fig. 2. As the students work

Fig. 1 Two introductory scenes of the DIMEG 'Zottel: the circus goat' (pictures drawn by Malin Emming)

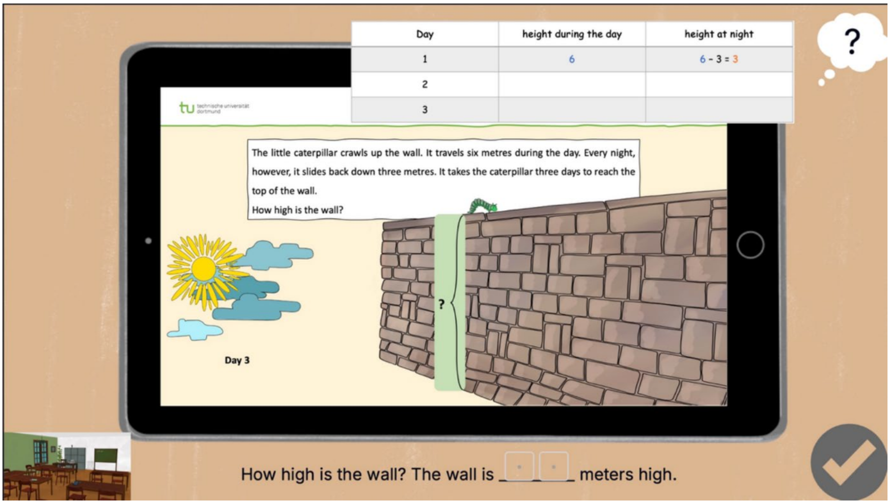

Fig. 2 An exemplary problem-solving task from the DIMEG 'Zottel' with the first hint

on tasks of varying complexity and interact with the game, they might need support in finding or solving the tasks (Fotaris & Mastoras, 2022). Thus, support appears, for instance, automatically after clicking on a help button or after a certain period of time. In the example in Fig. 2, the hint "Think carefully. How often does the caterpillar climb back up? And how often does it slide back down again?" appears after clicking on the question mark. When students enter the solution, they receive feedback on its correctness. In case of an incorrect solution to the problem in the DIMEG Zottel (Fig. 2), students are provided a table as a scaffold to regulate their problem-solving process and to offer a suitable heuristic (Herold-Blasius et al., under review). Due to the time constraints in an DIMEG, there are two possible outcomes: Either players complete all (problem-solving) tasks within the time limit, or they do not. Hence, they either free Zottel within the given time of 20 min or they do not which would possibly result in the cancellation or a delay of the circus presentation.

Summing up, digital educational games and also EG have been researched from various perspectives with regard to education. Studies report positive as well as negative results when playing those games with students of diverse ages (e.g., Bottino et al., 2007; Boyle et al., 2016; Hung et al., 2018; Qian & Clark, 2016; Wouters et al., 2013). However, when implementing such games in a school context, it is of crucial importance that pre- and in-service teachers are appropriately prepared and trained to integrate them into their teaching. This is true also because technical aspects and educational objectives of games should be in line with students' individual level of performance and curriculums. Furthermore, teachers need to acquire the knowledge to integrate digital games appropriately as well as the ability to assess and adapt the complexity of the problems posed in the games (Arosquipa Lopez et al., 2023).

Game Development-Based Learning in Teacher Education

Not only playing games has proven to be effective for learning but also designing them. In the educational context, the designer has to intensively engage with a subject-specific content and integrate it into the (digital) game as problem-solving tasks. Within this process, the designer becomes a problem-solver himself (Kafai, 1996; Wu & Wang, 2012). Compared to playing games, Vos et al. (2011) confirm that this design process is very motivating and enhances deep learning. Designing a game (also called game development-based learning (GDBL)) allows a more constructivist learning approach, is a more meaningful and engaging student activity, and is particularly characterized by authentic problem-based learning (Kafai, 1996; Vos et al., 2011; Wu & Wang, 2012).

Designing digital games was primarily integrated into teaching programming and computer science to secondary school students (Bewer & Gladkaya, 2022; Kafai, 1994, 1996), but it is now a method in diverse fields that promotes the enhancement of subject-specific content of different curriculums in a motivating and successful way (Wu & Wang, 2012; Yang & Chang, 2013). Thus, GDBL became not only a method for teaching students in school but also for educating pre-service and in-service teachers in order to foster all facets of TPACK through "learning by designing" (Koehler & Mishra, 2005; Koehler et al., 2007; Mishra & Koehler, 2003, 2006). In their study with in-service teachers designing a game about fractions, Kafai et al. (1998) conclude that "they [have to think] both about designing and playing concurrently. The designer must at the same time be a teacher and a learner. From our perspective, this affords opportunity for powerful professional development for teachers" (p. 178).

Regarding PST education, engaging intensively with the content as well as didactical, game-specific, and technological aspects while developing a digital game for a certain group of students constitutes an authentic situation to improve their technological skills in conjunction with pedagogical and content-specific aspects (Liu, 2021; Romero & Proulx, 2018; Vu & Gaskill, 2018).

In their systematic literature review on technology-supported problem-based learning in mathematics education for PST, Kirabo et al. (2024) describe equal effects and benefits. PST learn how to design and implement authentic, (not too) challenging, curriculum-aligned, engaging problems and choose the right technological tools that they are able to use adequately. Simultaneously, they experience the necessity of pedagogical strategies as well as facets of PCK (e.g., scaffolds and guidance for students) (Kirabo et al., 2024). Instead of learning about TPACK in theory, technology-supported problem-based learning like GDBL allows PST to use it in an active manner (Kirabo et al., 2024; Meletiou-Mavrotheris & Prodromou, 2016). Beyond that, it also provides the development of 21st-century skills as well as becoming familiar with the teacher's new "role as the facilitator of instruction" (Sardone & Devlin-Scherer, 2009) in the context of digital media (Li et al., 2013; Weisberg et al., 2022). Based on the teaching and learning style, PST regard to be most effective for their acquisition of digital competences, the GDBL approach meets their expectations: it allows active, creative, collaborative, (teacher) student-centered, and reflective learning (Göltl et al., 2024).

Taking a look at the design of EG as (pre-service) teachers' professional development opportunity in particular, the need for research in this field becomes obvious. There are still some studies which confirm the digital games' positive impact on teachers' learning. For instance, Weisberg et al. (2022) qualitatively examined PSTs' design processes of digital EG for diverse content areas and grade levels in the secondary curriculum. They found that PSTs' TPACK development, 21st-century skills and their perception and intention of technology integration are promoted through designing digital EG (Weisberg et al., 2022). However, since it was an interdisciplinary educational technology course and PST could choose the content individually, no mathematical specific game was designed. Also, Şahin (2023) conducted a study with primary school PST who designed a digital escape room and indicate that game development was „engaging, directed attention toward the profession [and] supported collaboration" (p. 940). The digital escape rooms were developed for a language course, though, and the study does not explicitly examine PSTs' knowledge or competence development.

In another design-based research study conducted by Piñero Charlo et al. (2021), PST created educational escape rooms (EER) to foster mathematical competences not only among themselves but also among primary students. The results indicate that the co-designing of the EER with in-service teachers "fosters the development of the trainee teachers' professional skills, mobilizing specific professional didactic-mathematical knowledge" (Piñero Charlo et al., 2021, p. 21). However, the EER are not technology-based.

In sum, research has shown that the design of digital games constitutes a substantial learning opportunity for teachers' professional development since it promotes the acquisition of the facets of TPACK and 21st-century skills among others. Yet, the literature review only led to studies presenting the design process of digital EG that focus on other subjects beside mathematics or EER that are math-specific but analog. To our knowledge, it has therefore not been investigated how PST develop math-specific knowledge facets within TPACK through designing DIMEG.

Research Interest and Questions

Research has shown the positive impact of digital games, and especially of EG for mathematical learning processes not only of students but also of (pre-service) teachers. The problem-based and authentic design of games requires PST to activate comprehensive knowledge for teaching and address diverse competences. Thus, GDBL has proven to be an effective approach for PST to enhance their teaching competences whereby developing digital games in particular fosters the facets of TPACK.

However, it has not been explored whether or how the design of DIMEG fosters the development of the knowledge facets of TPACK among pre-service mathematics teachers. Therefore, this study aims to address this gap by specifying the potential of digital educational EG within university education for PST. It qualitatively examines PSTs' self-reported development of the TPACK facets through creating their own DIMEG. For this, the following research question will be addressed in this article:

What learnings and challenges regarding pre-service mathematics teachers' facets of knowledge within the TPACK framework do they report after designing a DIMEG?

Methodology

To answer this research question, an exploratory, qualitative study with PST was conducted using an online questionnaire. Statements were categorized using qualitative content analysis and grouped according to the knowledge facets of the TPACK framework.

Context of the Study

Design of the Seminar

This study is based on a seminar developed for PST (primary and secondary) at the end of their bachelor's or master's degree program. Within the seminar, the PST designed and tested DIMEG with primary or secondary students. The seminar is structured into five sections (Table 2).

Table 2 Seminar sessions and their content

Session	Description of content
1./2.: Theoretical introduction	• DIMEG: definition, characteristics, criteria • game-based learning: definition, benefits for learning • problem solving: definition, heuristics, criteria of good problem-solving tasks • twenty-first century skills and curricula: competences that students should acquire when working on digital mathematical EG in teams • experience a game: playing one or two DIMEG
3. – 5.: Designing a DIMEG	• planning: nine steps to follow when planning an DIMEG, groups of students plan their game • implementation: presentation of technical possibilities (apps, learning platforms, genial.ly, Google Slides, …), technical implementation of the ideas
6. – 8.: Peer-feedback exchange	• in each session, groups of PST present their game, the other peers give feedback
9. – 10.: Test the DIMEG in classrooms	• PST use their games in a real classroom context with an appropriate age group
11. – 12.: Evaluation	• classroom evaluation: PST evaluate their experience in the classroom • game evaluation: PST derive design changes for their games from the classroom evaluation • seminar evaluation: PST give feedback on the seminar and fill in the questionnaire about their learnings and challenges

Participants

The seminar was held at three German universities (University of Duisburg-Essen, University of Siegen, and TU Dortmund University) in the summer term of 2023. 58 PST (primary: 18, secondary: 40; 39 female, 18 male, 1 diverse) of a bachelor's (2) and master's (56) program participated in this study. They chose the seminar voluntarily and, at the end, either wrote a reflective term paper or their master's thesis.

Data Collection

In the last session of the seminar (Session 12, Table 2), all PST participated via an online-based questionnaire in LimeSurvey. For this study, the open-response items on the topics of "learnings" and "challenges" form the data for analysis (Table 3). 56 of the 58 participating PST answered at least one of these items, resulting in 471 answers (learnings: 224; challenges: 247).

Data Analysis

The two topics "learnings" and "challenges" are analyzed separately using inductive category development (Mayring, 2000). To ensure intersubjectively comprehensibility and to match scientific standards (e.g., objectivity and reliability), the analysis followed a five-step procedure, which is described and illustrated in one example (Table 4).

(1) *Identification of answers and statements:* Unanswered items or items with an unspecific answer (e.g., "/"), are eliminated. This resulted in 429 informative answers (learnings: 200; challenges: 229). Each answer is paraphrased. If an answer contains different aspects, its content is divided into smaller statements

Table 3 Items "Learnings" and "Challenges" used in the online questionnaire

Topic	Items used	Type of item
Learnings during the design process	• What did you learn from designing your DIMEG in terms of your ◦ didactic competences? ◦ subject specific competences? ◦ digital competences? • What else have you learned from designing your DIMEG?	• open response
Challenges during the design process	• What challenges did you experience when designing your DIMEG in relation to ◦ the story? ◦ the tasks? ◦ the digital implementation? ◦ your own competences? ◦ using your escape game with students?	• open response

Table 4 Stepwise building and clustering of categories "learnings (L)" exemplified on one answer

Step 1:		Step 2:	Step 3:	Step 4:
Identification of answers and statements		Step-by-step formulation of inductive categories	Revision of categories and summarizing main categories	Deductive clustering according to the TPACK framework
"In relation to escape games I have learned to question every element of the game. ´Why, what, is this useful or necessary?´ I also learned the meaning of game-based learning I also learned about the structure of problem-solving tasks." (ID55)	"In relation to escape games I have learned to question single elements of the game. ´Why, what, is this useful or necessary?´" (ID55)	DIMEG	L10.2: medium-specific design aspects	TPCK
	"I also learned the meaning of game-based learning." (ID55)	game-based learning	L08: potential of digital media for teaching	TPK
	"I also learned about the structure of problem-solving tasks" (ID55)	problem-solving tasks	L04.2.1: structure of problem-solving tasks	PCK

which resulted in 512 statements (learnings: 250; challenges: 262) (see Table 4 for an example).

(2) *Step-by-step formulation of inductive categories:* For each statement a general, inductively generated category is formulated. Similar statements are grouped into one category.
(3) *Revision of categories and summarizing main categories:* In a feedback loop the authors ensured that the categories remained within the focus of the analysis. Some categories are summarized to main categories or specified by subcategories.
(4) *Deductive clustering according to the TPACK framework:* All main categories are assigned to the knowledge facets from the TPACK framework (L01–L10.4; C01–C08) or other overarching competences (L11–L13; C09–C11).
(5) *Interpretation:* The result of this five-step procedure is a category system (learnings: Tables 5, 6 and 7; challenges: Tables 8, 9 and 10). On this basis, quantitative aspects and frequency analyses complement qualitative analyses.

All of these steps were realized by the authors. Difficult category formulation or clustering was discussed within this group and decided consensually (Döring & Bortz, 2016).

Results

According to the research question, this part is structured in self-reported learnings and challenges.

Self-Reported Learnings Concerning the Knowledge Facets of the TPACK Framework

The PST provided 250 statements reflecting learnings across TPACK facets when designing DIMEG. Nevertheless, there is a clear focus on PCK (78), TPCK (60), and TK (71) (Fig. 3).

A Qualitative Insight on CK, PK, and PCK

Table 5 gives an overview of all inductively generated categories without technological components and how they were clustered into CK, PK, and PCK. There is a clear dominance in statements clustered to PCK, which was distinguished into two main categories (L03, L04).

The majority of PST reported learnings pertained to *problem-solving tasks* (L04), a core element in the design of DIMEG. This category encompasses the *selection* (L04.1) and *design* (L04.2) of problem-solving tasks. Given the varied emphases in PSTs' statements on the design of problem-solving tasks, six subcategories emerged: learning about the *structure* (L04.2.1), e.g., "I got to know the structure

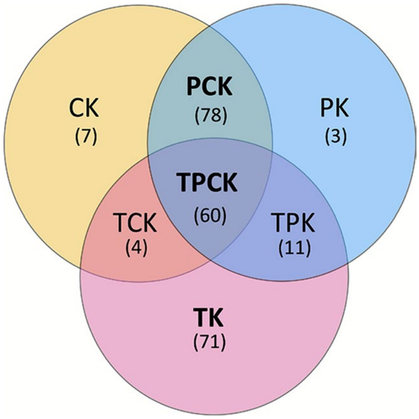

Fig. 3 Number of statements about learnings according to the TPACK facets

of problem-solving tasks” (ID-L-55); their *development* (L04.2.2), e.g. “I also got to know how tasks can be converted into problem-solving tasks” (ID-L-55); their *focus on students* (L04.2.3), e.g., “The level of difficulty must be strongly adapted to the respective learning group” (ID-L-33). Additional subcategories included the formulation of *task description* (L04.2.4), establishing a task’s *reference to the narrative* (L04.2.5) and the integration of *tips and assistance* (L04.2.6). Collectively, PST reported learning to design tasks that address student heterogeneity, and incorporate content-specific instructional support.

Table 5 Overview of non-technological categories concerning the learnings (L01–L04)

Category	Description of category	Number of statements (and PST)
	CK (7 statements, 7 PST)	
L01	mathematical content	7 (7)
	PK (3 statements, 3 PST)	
L02	learning process of students	3 (3)
	PCK (78 statements, 45 PST)	
L03	evaluation of students’ performance	12 (11)
L04	problem-solving tasks	66 (42)
L04.1	selection	11 (9)
L04.2	design	55 (38)
L04.2.1	structure	10 (10)
L04.2.2	development	13 (13)
L04.2.3	focus on students	12 (12)
L04.2.4	task description	9 (7)
L04.2.5	reference to narrative	4 (4)
L04.2.6	tips and assistance	7 (7)

PST also reported on the *evaluation of students' performance* (L03). They described increased awareness of assessment challenges, noting, e.g., that "[s]tudents are often overestimated in simpler tasks" (ID-L-30). In regard to CK, some PST referred to a subject-specific engagement with *mathematical content* (L01), prompted by the need to determine mathematical content for their DIMEG. This led to the deepening or refinement of existing knowledge. Only three PST reported learnings associated with PK, particularly concerning the *learning process of students* (L02), e.g., they note the importance of "responding to the students and encouraging them even if they are not making progress" (ID-L-53).

A Qualitative Insight on the Technological Knowledge Facets

PST reported learnings across all technological knowledge facets (Table 6), albeit with varying frequencies (TK: 71, TCK: 4, TPK: 11, TPCK: 60).

Within TK, two main categories emerged: *development of digital competence* (L05) and *using digital tools* (L06). In L05, PST reported an improvement in their digital skills and knowledge and identified a learning need, e.g., "I have not talked about digital media in my university course yet, so I took a lot with me" (ID-L-63), or "I have learned that I need to develop my digital competence further. […]" (ID-L-12). Statements in L06 comprise explicit mention of learning about and getting to know various tools in general and about using various tools, especially for designing EG, e.g., "I learned how to work with genial.ly and use it to implement an escape game technically. I worked with artificial intelligence to create images, which taught me what is important when creating images in a target-oriented way" (ID-L-48).

Table 6 Overview of technological categories concerning the learnings (L05–L10)

Category	Description of category	Number of statements (and PST)
	TK (71 statements, 49 PST)	
L05	development of digital competence	12 (11)
L06	using digital tools	59 (42)
	TCK (4 statements, 4 PST)	
L07	digital implementation of content	4 (4)
	TPK (11 statements, 11 PST)	
L08	potential of digital media for teaching	5 (5)
L09	application criteria and restrictions of digital media for teaching	6 (6)
	TPCK (60 statements, 37 PST)	
L10	DIMEG	60 (37)
L10.1	evaluation of digital EG and criteria for their integration into teaching	33 (25)
L10.2	medium-specific design aspects	16 (15)
L10.3	developing digital problems-solving tasks	5 (5)
L10.4	use of DIMEG in the classroom	6 (6)

TPCK is addressed with 60 statements made by 37 PST. They reported learnings about the *DIMEG* (L10) reflecting on diverse aspects when designing DIMEG and teaching with them. Four subcategories emerged (Table 6) of which the *evaluation of digital EG and criteria for their integration into teaching* (L10.1) was most frequently mentioned. PST identified various application options of DIMEG, such as “a good opportunity to repeat or deepen mathematical content” (ID-L-14) or as a “method of control or assessment” (ID-L-15). Nonetheless, they recounted the “time-consuming design” (ID-L-61) as well as the “technological requirements which are to be met” (ID-L-24). Thus, PST recognizing the potential as well as the limitations, e.g., “Digital media open up many possibilities that would be difficult to realize without them. However, digital media are not necessarily better than other media. One must be well acquainted with them in order to get their full potential” (ID-L-49).

This is also connected to the learnings about the *medium-specific design aspects* (L10.2) which comprise each single element of the EG and their interplay. PST reported that they got to know the importance of their games’ details for the learning process and the game flow, e.g., “I have learned to question every element of the game” (ID-L-55) or “the focus should rather be on the tasks than on a perfect story” (ID-L-56).

In addition, some PST reported learnings regarding the digital implementation of problem-solving tasks (L10.3), e.g., by getting to know “[h]ow many digital options there are of an interesting math task which can be integrated into (general) lessons beside the escape games” (ID-L-33).

When *using their digital EG in the classroom* (L 10.4) with students (see ‘Methodology’), some PST experienced individual approaches of the students and the students’ heterogeneity and time needed to solve the tasks, e.g., “[…] each group of students is different and depending on their class, age, etc., their behavior is different when doing the escape game.” (ID-L-55).

Learnings related to TCK and TPK are reported only by a few PST. The TCK category *digital implementation of content* (L07) includes statements in which PST described that they learned how to implement a specific mathematical content with a digital tool. Concerning TPK, the *potential of digital media for teaching* (L08) was reported as a learning. By creating digital EG, PST “learned that there are many digital tools that teachers can use for teaching” (ID-L-53), and that “[they] learned about the meaning of game-based learning” (ID-L-55). PST also identified *application criteria and restrictions of digital media for teaching* (L09), which encompass general classroom conditions, like data protection and licensing, as well as the use of non-educational digital media and programs for teaching.

A Qualitative Insight Into Further Competences

Besides the reported progress in their knowledge, some PST mention improvement in further competences through the design of DIMEG (Table 7). Regarding *interpersonal competences* (L11), some reflect on the collaboration during design process since they had to work in groups (e.g. “Teamwork. […]” (ID-L-26)).

Table 7 Overview of further, non-TPACK categories concerning the learnings (L11–L13)

Category	Description of category	Number of statements (and PST)
	Other (16 statements, 13 PST)	
L11	interpersonal competences	8 (8)
L12	interdisciplinary competences	5 (4)
L13	no learnings	3 (3)

Furthermore, few PST mentioned an improvement in their reflective competence („After playing the escape game [with students], I was able to reflect on and analyze my results" (ID-L-46)) and "flexibility" (ID-L-22) as competences required in diverse fields. These statements are summarized as *interdisciplinary competences* (L12). Three PST reported *no learnings* (L13) at all.

Self-Reported Challenges: An Overview of the Knowledge Facets of the TPACK Framework

Of the 262 statements reporting challenges, the majority of challenges were reported in PCK (102) and TK (56), whereas none were found concerning TCK and TPK (Fig. 4). Hence, when designing and implementing DIMEG, PST do not report challenges in all knowledge facets and report less challenges than learnings. Furthermore, the most frequently addressed facets (PCK, TPCK, TK) are the same as the ones in the reported learnings (Fig. 1).

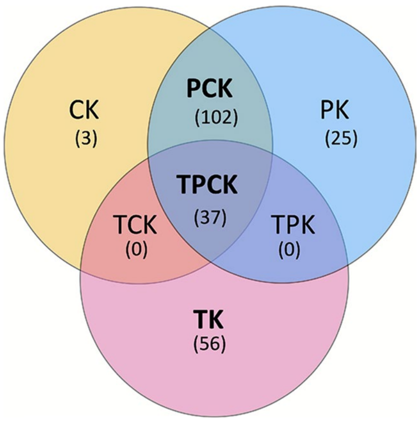

Fig. 4 Number of statements about challenges according to the TPACK facets

A Qualitative Insight on CK, PK, and PCK

PCK is the most frequently facet, in terms of both the number of statements and the number of PST reporting them (Table 8). The *evaluation of the students' performance* (C03) and the *problem-solving tasks* (C04) presented challenges. Statements in C03 point out that the PST were challenged when, e.g., "adapting the performance level to primary school and the heterogenous students" (ID-C-37).

The 84 statements with challenges concerning the *problem-solving tasks* (C04) were subcategorized based on different focuses. Challenges in the *selection* (C04.1), included the following: "It was difficult to find suitable tasks and to change them into good problem-solving tasks" (ID-C-66) and "to develop problem-solving tasks which should have a concrete solution in the escape game to be purposeful there" (ID-C-48). Besides, they were also challenged with the *design* (C04.2), particularly *linking tasks and narrative* (C04.2.5). The PST reported that „[e]mbedding the problem-solving tasks in the story is not always easy. You have to make sure that the numbers and statements in the problem-solving task also fit in with the story" (ID-C-12). The second most reported challenge is the *focus on the students* (C04.2.2) while developing or adapting tasks, as indicated by statements as "the challenge […] to estimate how easy or difficult the task is" (ID-C-17). The *development* (C04.2.1) of problem-solving tasks as well as an appropriate formulation of the *task description* (C04.2.3) and the integration of *tips and assistance* (C04.2.4) were also reported challenges by some PST, however, they only took a minor role.

Table 8 Overview of non-technological categories concerning the challenges (C01–C04)

Category	Description of category	Number of statements (and PST)
	CK (3 statements, 3 PST)	
C01	mathematical content	3 (3)
	PK (25 statements, 21 PST)	
C02	development of narrative	25 (21)
C02.1	focus on students	9 (9)
C02.2	narrative	16 (14)
	PCK (102 statements, 49 PST)	
C03	evaluation of students' performance	18 (15)
C04	problem-solving tasks	84 (46)
C04.1	selection	14 (14)
C04.2	design	70 (59)
C04.2.1	development	5 (5)
C04.2.2	focus on students	16 (14)
C04.2.3	task description	3 (3)
C04.2.4	tips and assistance	5 (5)
C04.2.5	linking tasks and narrative	41 (32)

Regarding PK, the PST made 25 statements on the difficulties in the *development of a narrative* (C02) which suits their DIMEG and makes it interesting. The narrative includes the whole setting and embedded story of the EG which should be designed pedagogical meaningfully and addressee oriented. PSTs' statements were categorised into two subcategories. Within the *focus on students* (C02.1), the PST reported the challenge of maintaining students' interests and performance levels. It was difficult for the PST "to put yourself in the students' shoes and think about what could arouse their interest" (ID-C-49) and to develop "[…] a story without integrating too much text to read" (ID-C-55). Regarding the *narrative* (C02.2), the PST described the difficulty of developing a narrative suitable for the game type 'escape game' "that makes sense and is close to reality" (ID-C-6). Only three statements referring to recognized gaps in the *mathematical content* (C01) were identified regarding PSTs' CK.

A Qualitative Insight on Technological Knowledge Facets

Challenges regarding the technological knowledge facets are allocated to two categories of TK and two categories of TPCK (Table 9). Referring to TK (56), the PST either described their (limited) general *digital skills and knowledge* (C05) as a challenge, e.g., "[My] technical competence is rather limited" (ID-C-38), or their ability to *use digital tools* (C06) when implementing DIMEG ("Until then, I knew very few digital tools. For example, I first had to work out the features of the various learning apps" (ID-C-22)).

The categories of the intertwining TPCK facet comprise the difficulties that arose during the *design process of DIMEG* (C07) and the challenges of *using DIMEG in the classroom* (C08). The design process is divided into the *graphical design* (C07.1) and the *technical design* (C07.2). C07.1 includes problems with the game's graphical design because pictures had to match the narrative and they had to be freely accessible. Challenges regarding the game's technical design can either be related to the *selection of tools and programs* (C07.2.1). Or they can also concern

Table 9 Overview of technological categories concerning the challenges (C05–C08)

Category	Description of category	Number of statements (and PST)
	TK (56 statements, 40 PST)	
C05	digital skills and knowledge	10 (9)
C06	using digital tools	46 (38)
	TPCK (37 statements, 28 PST)	
C07	design process of DIMEG	21 (20)
C07.1	graphical design	4 (4)
C07.2	technical design	17 (16)
C07.2.1	selection of tools and programs	3 (3)
C07.2.2	digital implementation of tasks	7 (7)
C07.2.3	restrictions in digital implementation	7 (7)
C08	use of DIMEG in the classroom	16 (15)

the *digital implementation of tasks* (C07.2.2), e.g., “Implementing the tasks digitally is difficult sometimes” (ID-C-36). Beyond that, PST reported *restrictions in the digital implementation* (C07.2.3), e.g., “LearningApps etc. often does not offer exactly what you need, rethinking is required!” (ID-C-26).

Watching and accompanying the students while they solve their self-developed EG (C08) confronted the PST with challenges beyond development. These included the struggle of following the students’ train of thought (“As game leader, it was difficult to follow the students’ train of thought without interfering too much with their process or asking questions” (ID-C-55)), of intervening or not (“The challenge for me was to recognize to what extent I was allowed to intervene in what was happening or to change the previously created instructions in order to support the group of students” (ID-C-48)), and the realization of a miscalculated management of time (“That the time management that we had previously planned or calculated was not applied in reality. The students need significantly longer to implement the project than previously planned, which has also led to frustration” (ID-C-47)).

No self-reported challenges regarding TPK and TCK could be identified. Regarding TPK, this resulted from the fact that PST did not choose an appropriate technology for the classroom by themselves. Instead, the technology was integrated in the DIMEG and thus, given to them. Concerning TCK, the reason might be that PST mainly encountered and reported challenges in the digital implementation of mathematical content regarding the story, tasks, and didactic aspects. They did not report challenges concerning only the technological representation of the mathematical content.

A Qualitative Insight into Further Competences

In addition to the knowledge facets, challenges related to *interpersonal and intrapersonal competences* (C09) – recognized as key skills in frameworks such as DigCompEdu–were identified (Table 10). PST reported challenges in teamwork and in perseverance which are common challenges of PST classroom teaching in general, and not specific to a technology environment.

Two PST described challenges concerning the *seminar* (C10) organization itself, more precisely the seminar’s requirements and the allocation of the groups, and 33 PST reported *no challenges* (C11) during the seminar or the design process of their DIMEG at all.

Table 10 Overview of further, non-TPACK categories concerning the challenges (C09–C11)

Category	Description of category	Number of statements (and PST)
	Other (41 statements, 25 PST)	
C09	interpersonal and intrapersonal competences	6 (5)
C10	seminar	2 (2)
C11	no challenges	33 (20)

Discussion

The aim of this study was to specify the potential of designing DIMEG in PST education from a qualitative perspective. It was found that PST reported learnings in all facets of TPACK and challenges in all facets except TPK and TCK.

Self-Reported Learnings when Designing a DIMEG

The findings reveal that PST reported learnings in ten categories aligning with TPACK facets, and three additional ones. Most statements pertained to TK and the intertwining facets of PCK and TPCK, suggesting that developing DIMEG supports TPK development – a result consistent with prior research on GDBL in other subjects (Şahin, 2023; Weisberg et al., 2022) and technology-supported problem-based learning in mathematics education (Kirabo et al., 2024). Within PCK, PST emphasized evaluating student performance and selecting and designing problem-solving tasks (L03, L04; Table 5). These activities required adopting learners' perspectives, adapting task levels and descriptions, and offering appropriate assistance – processes similar to problem-posing processes involving creativity, content knowledge, and pedagogical reasoning (Baumanns, 2022, 2023). The prominence of the category design (L04.2) of problem-solving tasks, with 55 statements and six subcategories (Table 5), underscores the complexity and centrality of this aspect. PST demonstrate awareness of how students might engage with tasks, potential difficulties, and necessary concepts. In the context of GDBL, the process of developing problem-solving tasks functions as an authentic problem-based learning for teachers, fostering deep learning and reflection (Kafai, 1996; Vos et al., 2011; Wu & Wang, 2012).

Within TK and TPCK, the PST reported diverse learnings when creating and teaching with DIMEG. In line with, e.g. Göltl et al. (2024), Gabarda Méndez et al. (2023), and Ständige Wissenschaftliche Kommission der Kultusministerkonferenz (SWK, 2022), many statements (L05–L09; Table 6) highlight deficits in technological knowledge. PST became aware of their individual development needs (L05) and gained valuable experience with digital tools during the design process (L06), enhancing both PSTs' competence and self-perception as learners (Deci & Ryan, 2000). Their targeted and reflective engagement with digital technologies also led to a critical awareness of technology's affordances and limitations (L08, L09).

With regard to TPCK, the findings indicate that designing DIMEG offers a valuable opportunity to foster PSTs' integrated professional knowledge (L10). The high number of 78 statements in PCK underscores the complexity of designing problem-solving tasks, which demands close engagement with content, methods, and students. When technological components are added, the design process becomes even more demanding. Our results show that PST actively developed TPCK by critically evaluating technological features and their educational potential (L10.1, L10.2), and by designing meaningful tasks that leverage technology to support both teaching content and the students' learning process (L10.3) (Kirabo et al., 2024; Mishra & Koehler, 2006; Şahin, 2023; Weisberg et al., 2022). Additionally, requiring PST to develop their own DIMEG from scratch, encouraged a deeper examination of the pedagogical value, content structure, game characteristics and students' abilities. This process promoted a reflective stance towards the affordances and constraints of digital education games. Implementing their games in the classroom (L10.4) created an authentic learning context that not only heightened PSTs' sensitivity to student heterogeneity but also fostered intense reflection of their own decisions regarding their games' and tasks' design (Kirabo et al., 2024).

Beyond knowledge facets for teaching, the design process of DIMEG also promoted inter- and intrapersonal competences (L11, L12). Not only playing, but also designing DIMEG seem to foster collaboration, teamwork and communication skills – competences emphasized in DigCompEdu (Redecker, 2017) and the 21st century skills framework (Qian & Clark, 2016; Trilling & Fadel, 2009).

Self-reported Challenges When Designing a DIMEG

With regard to the challenges reported by PST, 10 categories were identified and assigned to the TPACK facets. The challenges align with previous research on game design and GDBL (e.g., Botturi & Babazadeh, 2020; Devlin, 2011; Nicholson, 2015; Piñero Charlo et al., 2021; Qian & Clark, 2016) and are closely linked to reported learning gains. For instance, uncertainties in their content-specific knowledge (C01) led PST to revise and deepen their mathematical knowledge about a specific topic (Kafai et al., 1998) so that they reduced these deficits and overcame the challenges (L01). Crafting an interesting and pedagogically sound narrative posed further challenges (C02), revealing the complexity of designing education materials from scratch. While meaningful storytelling fosters immersion and game flow (Botturi & Babazadeh, 2020; Devlin, 2011; Qian & Clark, 2016), it can shift focus away from mathematical content and its pedagogical quality which underlines the need for structured instruction and support during game development.

In PCK, the PST faced challenges in developing problem-solving tasks adapted to students' needs and with integrated assistance (C04). Yet, overcoming these challenges leads to valuable learnings (Kafai et al., 1998; Kirabo et al., 2024). Integrating these tasks meaningfully into a game's narrative emerged as a typical challenge (Botturi & Babazadeh, 2020; Devlin, 2011; Nicholson, 2015) requiring the interplay between PK, CK, and TPCK. Technological challenges were particularly prominent (93 statements), highlighting heterogeneous levels of PSTs' prior knowledge concerning technology for teaching (Gabarda Méndez et al., 2023; Göltl et al., 2024; Romero & Proulx, 2018; SWK, 2022; Takeuchi & Vaala, 2014; Vu & Gaskill, 2018). Some PST reported a lack of digital competence (C05–C07), including difficulties in selecting appropriate digital tools (C06), in sourcing open-access media (C07.1) or in implementing the problem-solving tasks (C07.2). However, these challenges also fostered critical reflection on digital teaching competences (Redecker, 2017). The implementation of DIMEG with students (C08) created authentic teaching experiences, prompting reflection on the game's design process (Göltl et al., 2024; Kirabo et al., 2024). In addition, collaboration and communication posed inter- and intrapersonal competences (L11, L12) and challenges (C09). This shows that such competences are both fostered and required during collaborative GDBL (Redecker, 2017; Trilling & Fadel, 2009).

Surprisingly, no challenges were reported in TCK or TPK. This might, of course, reflect the fact that no PST reported them, possibly because they reported them at some other point and thus, in a different category. However, it might also reflect a deficiency in the data gathering process as it seems unlikely that PST did not encounter any challenges in these category – especially as some of them described themselves as rather naïve to the use of technology (C05–C07).

In sum, the challenges PST encountered, particularly regarding problem-solving task design, narrative integration, and digital implementation, were key to their reported learnings. The learning-by-design approach supported gains in TK, PCK and TPCK by offering an authentic context (Liu, 2021), content-specific aspects and its digital implementation (Liu, 2021; Romero & Proulx, 2018; Vu & Gaskill, 2018). Designing DIMEG thus activates all relevant knowledge facets and further key competences for mathematics teaching with digital media, making it a promising method for teacher education.

Conclusion

This contribution gives qualitative insights into PSTs' self-reported learnings and challenges in the context of TPACK when designing and testing DIMEG. The results indicate the diverse potentials of the GDBL approach using the example of DIMEG for the impartment of TPACK in teacher education. Yet, there are some limitations of this study to be considered. First, data collection is based on PSTs' subjectively assessed learning growth. Hence, their written answers are to be verified through observation, standardized knowledge tests, or interviews in a subsequent study. Particularly more detailed questions for PST who gave no answers or did not perceive any challenge should be integrated into interviews. Additionally, a data collection allowing a mixed-method analysis would support the results quantitively.

Second, although this study shows that the seminar has supported the development of TPACK, some necessary adjustments concerning the seminar concept have emerged. In order to improve the familiarization with new digital tools and to speed up the games' digital implementation, we recommend professional designer teams to support this process, e.g. student research assistants with expertise in digital tools, game design as well as illustrations. With their support, PST would be able to focus even more on the games' features and their interlocking with pedagogical and content aspects. Moreover, for an even more structured process, the design-model for EER of Botturi and Babazadeh (2020) should be integrated into future design processes. This model could help PST to get and keep a good overview of each of the games' elements and their interconnection while creating the story and adapting the content and tasks to a specific learner group.

Further research should not only analyze self-reports but also evaluate developed EG in terms of their mathematical and pedagogical quality as well as their impact on students' mathematical learning outcomes. Such evidence could underline that

GDBL does not only foster PSTs' TPACK but could also lead to meaningful and effective mathematical learning of students.

Overall, this study contributes to research on design-based approaches in teacher education and provides a valuable example of how game design can be used to engage PST in reflective, technology-related practice.

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Data Availability The participants of this study did not give written consent for their data to be shared publicly, so supporting data is not available.

Declarations

Ethical Approval All participants were provided an informed written content which they signed their written consent to participate in this study. An ethics approval was not required for this study.

Consent for Publication The signed written consent of the participants allows for the publication of research results.

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