# Proceedings of the Nineteenth ERME Topic Conference

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# *Connecting the Learning of Mathematics Teaching to Practice*

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# TPACK learning paths of pre-service teachers when designing digital mathematical escape games

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*Pre-service teachers (PST) need subject-specific, didactic and pedagogical knowledge for their future teaching practice, commonly described within the TPACK framework. The 'Digital Competence Framework for Educators' (DigCompEdu) emphasizes the importance of technical and digital skills for teachers in general. One way to address relevant knowledge facets for PST is through game development-based learning, which includes designing digital escape games. Yet, questions remain about which knowledge facets PST activate when designing a digital mathematical escape game (DIMEG) and how this develops throughout the design process. In this study, one group of primary school PST designs a DIMEG within a seminar. Each seminar session was videotaped, transcribed and coded towards TPACK knowledge facets. Findings from this study show that all knowledge facets were activated, except TCK, suggesting that DIMEG is a promising approach for teacher education.*

*Keywords: Game based learning, gamification, teacher education.*

## Introduction and theoretical background

The International Computer and Information Literacy Study (ICILS) 2023 found that nearly 70% of German teachers use digital media at least once per day in their teaching, which is 46,7% more than in ICILS 2018 but less than in other countries, e.g., Denmark or Norway (Eickelmann et al., 2024). One reason may be that digital and technological competences are not sufficiently addressed in teacher education. About one third of the teachers report that in their teacher education, 'approaches to support learning and teaching with digital media' was part of their teacher education, which is significantly less than the international mean (Eickelmann et al., 2024). Yet, in the digital age, those competences are crucially important (Redecker, 2017). Thus, already pre-service teachers (PST) need to acquire subject-specific content, didactical, pedagogical, and technological knowledge for their future teaching practice (Mishra & Koehler, 2006; Redecker, 2017). Those knowledge facets are commonly described within the Technological Pedagogical Content Knowledge (TPACK) framework (Mishra & Koehler, 2006). In the following, the framework and the development of its knowledge facets are explained and illustrated in the context of 'game development-based learning' (GDBL) (Wu & Wang, 2012) with digital mathematical escape games (DIMEG).

### TPACK framework and the development of knowledge facets

It defines and interconnects the seven different facets of teacher knowledge: CK (content knowledge), PK (pedagogical knowledge), PCK (pedagogical content knowledge), TK (technological knowledge), TCK (technological content knowledge), TPK (technological pedagogical knowledge), TPCK (technological pedagogical content knowledge) (Mishra & Koehler, 2006). The TPACK framework is the result of studies that focused on "how" teachers learn to teach with technologies instead of "what" they have to learn about these. Successful learning about teaching with technologies requires the equivalent consideration of each facet (technology, pedagogy, content) to emphasize technology skills as well as to develop a comprehensive TPCK (Mishra & Koehler, 2006).

Developing the knowledge facets of the TPACK framework of PST is an important goal of teacher education and professional development (Mishra & Koehler, 2006; Shambare & Simuja, 2024). Yet, the process of constructing and developing this knowledge remains largely unknown (Shambare & Simuja, 2024). Only a few studies explore the development of the knowledge facets in different contexts. Darkwa and Agyei (2021) investigated how eight PST developed their TPACK by designing and implementing audio-visual supported lessons. They conducted a sequential multiple case study and showed an improvement in all knowledge facets, whereby the largest was in technology-related facets (TPCK, TPK, TCK and TK). They highlight that PST tried a combination of the three core knowledge facets (technology, pedagogical and content) and not only developed their TPCK. Shambare and Simuja (2024) discuss the integration of technology in rural education settings and show that non-technology-related facets scored higher in terms of mean. Therefore, they suspect that combining technological understanding with content and pedagogy is challenging. There are also studies investigating the perception of TPACK and the connections between single knowledge facets using statistical path analysis. For example, Koh et al. (2013) explored how the individual knowledge facets of teachers in Singapore are interrelated. They demonstrate that teachers view TPACK as stemming from the direct effects of PK, TK, TCK, and TPK, where TCK and TPK have stronger effects, and confirm the strong correlations between the technological facets.

Methodologically, studies focusing on the development of the knowledge facets use surveys (Koh et al., 2013) or conduct a pre-post-test design (e.g., Darkwa & Agyei, 2021). Yet, self-reported methods may not accurately reflect the actual learning (e.g., Kosiol & Ufer, 2024). Thus, in this study, we use video observation to map the development of the TPACK facets.

**Game-development-based learning with escape games**

The development of educational technologies based on the concept of 'Learning-by-Design' provides an opportunity for (pre- and in-service) teachers to learn about technology and expand their knowledge facets (Mishra & Koehler, 2006). One way to implement this approach is to design games in the spirit of GDBL. GDBL allows a constructivist learning approach, provides a meaningful and engaging student activity, enhances deep learning, is highly motivating and particularly characterized by authentic problem-based learning (Vos et al., 2011; Wu & Wang, 2012). For this contribution, PST design their own digital escape game (EG). In an EG (or escape room), the players have to escape from an unpleasant situation or rescue someone from a predicament by discovering clues and accomplishing tasks collaboratively in teams within a limited amount of time. A central challenge is figuring out what the puzzle is about and how to solve it. To overcome these, clues and hints are included (Nicholson, 2015; Stohlmann, 2023).

In sum, GDBL is an effective approach to enhance PSTs' teaching competences and thus, knowledge facets concerning the TPACK framework. However, the activation of these facets and their development in the context of GDBL and EGs has been scarcely studied. Thus, in this study, we examine two research questions: (1) Which knowledge facets do PST activate when designing a DIMEG, and (2) How do these facets develop throughout the design process of a DIMEG*?*

## Methods

### Design of the study

This study was conducted within a seminar at TU Dortmund University (Germany) developed for primary school PST at the end of their bachelor's program in the winter term of 2024/2025. 14 PST participated (1 male, 13 female) and were grouped with 2 or 4 PST (a total of four groups) to design their own DIMEG. The seminar was structured into three main sections: (1) designing a DIMEG (e.g., task selection, narrative, game flow, storyboard, technical implementation), (2) game implementation with groups of primary school students in a real classroom and data collection, and (3) data analysis and writing the bachelor's thesis. The design process (sessions 1 to 6) was supported by a designer team consisting of four interdisciplinary students. They provided advice on various aspects, e.g., game or graphic design, and the technical implementation of the DIMEG within an online-based editor. Data was collected by videotaping sessions 2 to 6. Group discussions were videotaped for each group separately with four cameras and microphones. In addition, one camera captured the seminar room for the plenary phases. Session 1 was not videotaped because students mainly learned about organizational input, some theoretical background concerning mathematical problem solving, and escape games and played a DIMEG. Thus, they did not talk much with each other which is why little output concerning their knowledge activation was expected. For this contribution, video data of group A with four PST in sessions 2 to 5 is considered because their design process was especially rich and interesting concerning the activation of knowledge facets.

### Data coding and analysis

First, all data were transcribed using MAXQDA 24. Second, the transcripts were coded to identify the knowledge facets activated by the PST. Therefore, a category system was developed deductively (Mayring, 2000) (Table 1) and implemented in three steps:

1) Identify phase of the seminar: The seminar consisted of two phases: (a) *plenary phases* with input or exchange of ideas with all PST, or (b) working phases of the *group*.
2) Identify main action in the phase: Independent of the phase (group vs. plenary), there was (a) *input* by the lecturer or the designer team, or (b) *work* between the PST.
3) Identify knowledge facet: Each turn in the transcript was coded according to the seven *knowledge facets* (Table 1). To assign a turn to a category, existing categories and item descriptions were considered (e.g., Herold-Blasius et al., accepted; Kosiol & Ufer, 2024).

Additionally, other content of discussion (e.g., organizational topics concerning the bachelor's thesis or private information of the participants) was coded for reasons of completeness. However, those codes are not reported here due to the research focus.

To ensure intersubjective comprehensibility and match scientific standards (e.g., objectivity and reliability) (Mayring, 2000), two researchers coded the transcripts of the group separately. To measure intercoder reliability, the Kappa coefficient is applied (Landis & Koch, 1977). As full accordance among both coders cannot be expected – all coding involves interpretation – a value of 0.7 is considered sufficient. In this study, a value of 0.7 was reached in all sessions by both independent coders ($\kappa_2$: 0.73; $\kappa_3$: 0.84; $\kappa_4$: 0.93; $\kappa_5$: 0.92). To improve the intercoder reliability, the differences were discussed and validated consensually. This explains the increase from session to session. After coding, descriptive statistics with absolute and relative frequencies were realized, and a sequential representation of the order and distribution of the codes was generated with MAXQDA 24 to illustrate the development of knowledge facets within group A.

**Table 1: Category system**

| Knowledge facets | Categories (and subcategories) | Examples of coded statements from PSTs' work |
|---|---|---|
| CK | application of your own mathematical knowledge | That's a geometric body, isn't it? At least in terms of its shape, it's not a net. (GA, S2, turn 411) |
| PK | learning process of students; development of the narrative and game flow | I imagined that they were in a maze or something similar. Then, somehow, they ended up there, where they had to solve various tasks. (GA, S2, turn 311) |
| TK | digital competence; getting to know and using the online-based escape game editor | Could we arrange for the wizard to appear in a room when the time runs out? (GA, S5, turn 160) |
| PCK | learning objectives; curriculum, problem-solving tasks; tips and assistance | It could be something like matching puzzle pieces to their correct geometric body. That could be another task. (GA, S2, turn 71) |
| TCK | knowledge about potential applications and their use to represent content | / |
| TPK | criteria and limits for the use of digital media in the classroom | They probably don't use research tools. (GA, S2, turn 131) |
| TPCK | medium-specific design process, technical implementation of tasks and use of the game with students | I think determining and comparing the volume of solids using unit cubes is quite difficult in terms of technical implementation. (GA, S2, turn 88) |

## Results

### Activated knowledge facets when designing a DIMEG

To investigate, which knowledge facets were activated, Table 2 presents the descriptive statistics for each knowledge facet and seminar session of group A.

Table 2 shows that PST activated all knowledge facets, except for TCK, with varying frequency. In total, 642 activations of knowledge facets were coded. Also, with each session, an increasing number of different facets are activated – PCK in session 2 vs. PK, TK, PCK, TPCK in session 4. This could indicate a kind of connectivity between the facets. Moreover, technological knowledge facets occur mainly in sessions 4 and 5, whereas core knowledge facets PCK and/or PK are frequently activated

**Table 2: Descriptive statistic of knowledge facets (absolute and relative frequency)**

| | session 2 | | session 3 | | session 4 | | session 5 | | total |
|---|---|---|---|---|---|---|---|---|---|
| CK | 4 | 2.5 % | 6 | 4.6 % | 0 | 0 % | 14 | 7.4 % | 24 |
| PK | 17 | 10.5 % | 54 | 41.2 % | 42 | 26.1 % | 15 | 8 % | 128 |
| TK | 8 | 4.9 % | 0 | 0 % | 24 | 14.9 % | 84 | 44.7 % | 116 |
| PCK | 121 | 74.7 % | 70 | 53.4 % | 36 | 22.4 % | 49 | 26.1 % | 276 |
| TCK | 0 | 0 % | 0 | 0 % | 0 | 0 % | 0 | 0 % | 0 |
| TPK | 5 | 3.1 % | 0 | 0 % | 0 | 0 % | 0 | 0 % | 5 |
| TPCK | 7 | 4.3 % | 1 | 0.8 % | 59 | 36.6 % | 26 | 13.8 % | 93 |
| total | 162 | | 131 | | 161 | | 188 | | 642 |

throughout all sessions. In session 3, the PST do not only select and adapt (problem-solving) tasks (PCK: 53.4 %), but also focus on developing a narrative and tell a story within the DIMEG (PK: 41.2 %). In sessions 4 and 5, the designer team actively participates in the seminar, and supports PST with advice about task selection, game or graphical design, and the technical implementation of the game. In these conversations, various topics occurred covering TPCK (36.6 % resp. 13.8 %), TK (14.9 % resp. 44.7 %), and PCK (22.4 % resp. 26.1%). Overall, two codes occurred only scarcely – CK, and TPK, while TCK was not observed at all.

This analysis indicates that first, many knowledge facets can be activated by designing DIMEG, and second, the knowledge facets are not only activated sequentially, but rather in combination with each other and possibly connected.

**Development of knowledge facets throughout the design process of a DIMEG**

To analyze the development of the PSTs' knowledge facets throughout the DIMEG design process, all codes are represented sequentially for seminar sessions 2 and 5 (Figure 1). This chronological representation (x-axis) provides an overview of the codes (illustrated with colors according to Table 1) used in these sessions (y-axis). It shows all three steps of the coding procedure (see Methods): (1) the phase of the seminar (grey bars); (2) the input or work phase, and (3) the activated knowledge facet coded. When a code is assigned to a statement, the code's color is displayed in the corresponding column.

Table 2 shows that PST focus on different knowledge facets during the sessions. Comparing them, please note that the input corresponds to the PSTs' focus (Figure 1). In other words, the focus of input in each seminar session is reflected in the activated knowledge facets (e.g., see session 2). The PST focus on task selection, and primarily activate PCK in session 2 by raising this as a topic during the first group phase (Figure 1). The subsequent plenary phase addresses precisely the aspects raised by the PST – task search and task analysis. This encourages them to carry on working on this topic throughout the session. We conclude that PST dealt with the topics of each session, and regularly enriched this by activating additional knowledge facets. Therefore, the changes in sessions 2 and 3 in the activated facets (Table 2) during the sessions could be related to the focus of each session.

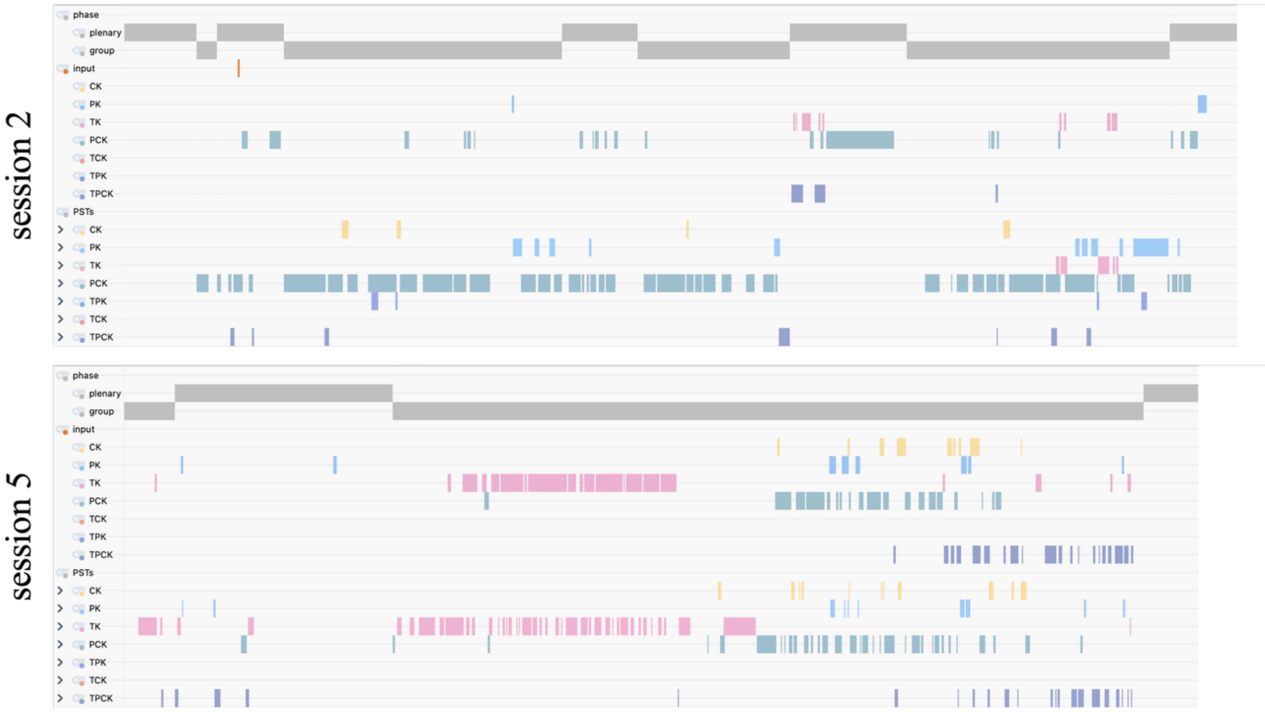


**Figure 1: Activated knowledge facets in seminar sessions 2 and 5**

Furthermore, the facets are not activated sequentially, but alternately (Figure 1). Moreover, PST repeatedly pick up on knowledge facets from previous sessions, and connect them with new facets. Thus, more knowledge facets are activated from session 2 to session 5. Also, the different knowledge facets are increasingly interconnected, which is indicated by the alternating change of colors, and thus, a change of the knowledge facets (Table 2 and Figure 1). In sessions 4 and 5, the designer team supported PST in the design process for their DIMEG. Various facets of knowledge are activated in those sessions. Longer sections of the same knowledge facet indicate conversations with members of the designer team. TPCK mainly occurred in session 4. Both, Table 2 and session 5 in Figure 1, indicate that this time of the design process in combination with the support of the designer team fosters the interconnection between knowledge facets.

## Discussion and conclusion

This study aimed to investigate which knowledge facets PST activate when designing DIMEG and how these develop during the design process. The results indicate that designing a DIMEG allows PST to activate all knowledge facets, in this particular group, except for TPK. This supports results from earlier studies in the context of GDBL (Mishra & Koehler, 2006; Piñero Charlo et al., 2021; Wu & Wang, 2012). Yet, in sum, there are lower scores for all technology-related knowledge facets (TK, TPK, TCK and TPCK) than for all non-technology ones (CK, PK and PCK) (Table 2), which is in line with the results of Shambare and Simuja (2024). At the same time, PST activated different knowledge facets alternately and increased the number of facets, implying an increasing connection between them.

Different and unexpected from existing studies (e.g., Koh et al., 2013), PST in this study activated TPCK, without showing TCK and with five coded activations of TPK throughout all sessions. This might indicate that other ways could lead to the acquisition of TPCK. Further qualitative and quantitative investigations are needed to explore this observation.

Four main limitations of the study should be acknowledged. First, our results are not generalizable, as this study focused on one group only. Future studies should analyze more groups of PST. Second, PST were observed and videotaped during their seminar sessions. Neither interviews nor knowledge tests were conducted, mainly due to practical reasons. Yet, this could strengthen the design of the study. Third, the coding considered what PST said in each seminar session. Thus, what they thought or discussed outside the seminar could not be recorded. Hence, PST could possibly have activated more knowledge than we could code. Fourth, by providing an online-based editor to implement the DIMEG technically, we limited the range of available technologies. In future studies, this variety could be increased by adding artificial intelligence or integrating apps such as GeoGebra.

The design process of a DIMEG provides an opportunity to address the deficit of digital skills among PST (and teachers). For students to become more digitally competent, PST and in-service teachers must first be trained in these competences. From the results of this study, we conclude that designing and implementing escape games within a seminar of teacher education is a setting that provides a rich opportunity to develop (almost) all knowledge facets of the TPACK framework. The design of escape games is an effective way to introduce PST to technology in teacher education. These skills are essential for teachers to be able to use technology in their own teaching and to change conventional mathematics teaching. It remains unclear whether this can be transferred to other digital environments, such as the development of learning or explanation videos, or other content, such as biology or chemistry. Also, it would be interesting how PST can transfer their acquired knowledge for instance to reflect the quality of other DIMEG.

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