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The teaching-learning lab Digi-Space: A design-based research pilot on digital media integration in pre-service physics teacher education

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Abstract
Technology-rich physics teaching requires pre-service teachers to coordinate technical, content-related, and pedagogical knowledge. Yet empirical evidence on how novice teachers allocate attention across these domains during lesson design remains limited. This pilot study examines how pre-service physics teachers allocate time and attention while planning digitally enriched lessons, and which factors shape their resource use. Guided by the technological pedagogical content knowledge framework and the synthesis of qualitative evidence 2 model, we conducted a qualitative case study within a design-based research cycle. *N* = 16 pre-service physics teachers participated in a seminar. Data from pre- and post-surveys, learning diaries, and semi-structured interviews were analyzed using reflexive thematic analysis. Results show a strong asymmetry: planning was dominated by technical problem-solving, while pedagogical reasoning became increasingly marginal. Key influences were technical novelty, inconsistent self-organization, unclear task requirements, and reluctance to seek instructor support. The findings suggest that early and structured scaffolding may help prevent technical demands from overshadowing pedagogical reasoning.

Keywords: physics teacher education, pre-service teachers, digital media, maker technologies, TPACK, DBR

INTRODUCTION

Recent needs analyses and implementation studies in physics teacher education indicate a sustained requirement to systematically embed digital teaching and learning methods into curricula rather than treating them as add-ons (Henne et al., 2022; Weiler et al., 2023). Subject-specific competency frameworks such as DiKoLAN provide structured reference points for the development, assessment, and reflection of digital competencies in science teacher training and make it clear that integration must be anchored in subject content and pedagogy (von Kotzebue et al., 2021). Despite these frameworks and the increasing availability of powerful digital and maker technologies, pre-service physics teachers continue to underuse these resources in their lesson designs. A key challenge is that theory and practice are often treated separately: prospective teachers often learn to use tools without engaging in authentic, feedback-rich applications and structured reflections that consolidate the pedagogical, technological, and content orientation (Priemer & Roth, 2020). University learning laboratories that coordinate micro-teaching, observer roles, and systematic reflection have been proposed as one approach to bridge this gap by enabling iterative cycles of planning, implementation, evidence collection, and redesign with reduced complexity (Priemer & Roth, 2020). A simple explanation for the persistent shortfall locates the problem somewhere between the time required and the expertise needed to integrate such tools meaningfully, both of which should be systematically developed in pre-service teacher training.

How teaching and learning with digital media is informed by theory has been addressed from multiple angles. The technological pedagogical content

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Contribution to the literature

- This study provides process-level evidence on how pre-service physics teachers allocate time and attention across technical, content-related and pedagogical aspects when designing digitally enriched lessons.
- This study shows that high technical novelty, combined with open task structures and uneven self-regulation, can displace pedagogical reasoning even within a theoretically grounded technology-integration seminar.
- The findings of this study extend TPACK- and SQD-informed teacher education by identifying early technical stabilization, explicit task guidance, and accessible support as key design principles for maintaining pedagogical reasoning during technology-rich lesson planning.

knowledge (TPACK) framework models how technological, pedagogical, and disciplinary knowledge interact to enable informed, context-sensitive instructional design (Mishra & Koehler, 2006). Building on this knowledge architecture, the synthesis of qualitative evidence (SQD) model consolidates evidence-based preparation strategies for pre-service teachers, including role modeling, guided reflection, instructional design tasks, collaboration, authentic experiences, and structured feedback (Tondeur et al., 2012). The SQD instrument has been validated and demonstrates criterion-related validity with respect to TPACK-related outcomes, supporting the alignment of its dimensions with intended technology-pedagogy-content knowledge development (Knezek et al., 2023). The updated SQD2 synthesis retains these core strategies while foregrounding additional emphases that address the evolving digital landscape: the explicit use of instructional design models (e.g., backward design and constructive alignment), the cultivation of digital identity and professional agency, and affective-motivational supports for sustainable, context-sensitive integration (Tondeur et al., 2025). For teacher education, these emphases translate into portfolio-supported identity work, model-based planning templates that make pedagogical reasoning visible, and structured supports for self-efficacy, perceived relevance, and emotion regulation during technology-rich enactments (Tondeur et al., 2025). At the subject-specific level, DiKoLAN operationalizes science-specific digital teaching competencies by formulating performance levels and descriptors grounded in the TPACK architecture, making integration actionable within science teacher training (von Kotzebue et al., 2021). Related work with prospective science teachers likewise connects TPCK with scientific attitudes and basic science process skills, highlighting that technology-related teacher knowledge is embedded in broader disciplinary and professional competencies (Juhji & Nuangchalerm, 2020). Together, these frameworks address learning processes in technology-rich environments, the design of learning environments that foster digital competencies, and the acquisition of subject-specific digital teaching competencies (Mishra & Koehler, 2006; Tondeur et al., 2012, 2025; von Kotzebue et al., 2021).

This theoretical landscape has been translated into empirical implementations. DiKoLeP, a cross-university collaboration, instantiates SQD strategies within coherent course architectures, reporting pre-post gains in digitalization-related physics-didactics knowledge and favorable shifts in motivational orientations, with participants rating the presence and quality of SQD-aligned features highly (Weiler et al., 2023). DiKoLAN has been adopted as a mandatory reference framework for digital competency development in science teacher education (von Kotzebue et al., 2021). At the institutional level, learning laboratories that coordinate micro-teaching, observer roles, and systematic reflection aim to bridge theory and practice through iterative cycles of planning, enactment, and structured reflection (Priemer & Roth, 2020). Reflection in action and reflection on action are central to professional growth, transforming knowing in action into adaptive instruction (Schön, 1983). Research on learning laboratories indicates that they can support increases in professional knowledge, domain-specific teacher self-efficacy, and reflective skills, with emerging evidence on improvements in teaching performance under such iterative, feedback-rich designs (Rehfeldt et al., 2020). Technology-enhanced experimentation in physics benefits from interactive simulations that leverage dynamic visualizations and feedback to promote conceptual understanding (Finkelstein et al., 2006; Wieman & Perkins, 2005), and immersive technologies such as augmented reality (AR) and virtual reality (VR) can support engagement and complex visualization under well-designed integrations (Garzón & Acevedo, 2019; Radianti et al., 2020). Furthermore, technology-related self-efficacy has been shown to strongly predict perceived usefulness, perceived ease of integration, and intention to use digital media, whereas test-based TPACK contributes complementary effects (Lhotzky, 2023; Schubatzky et al., 2025). Complementary quantitative evidence from in-service high-school teachers suggests that digital literacy and teaching experience are significant predictors of pedagogical competence (Anggraini et al., 2024). Designs that combine SQD2 strategies with explicit TPACK development are therefore well positioned to raise both knowledge and the beliefs that translate knowledge into stated intentions for classroom

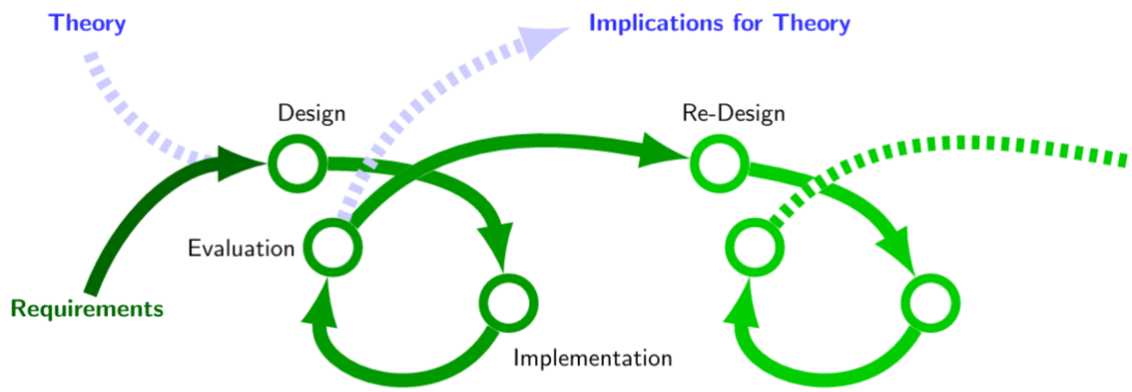

Figure 1. DBR process (adapted from Veith et al., 2022 and tailored to the context of our project). It functions as a structuring framework both for the overall research project and for the present paper. In this contribution, we focus on the first iteration of the DBR-cycle effectively piloting our concept. The illustrated iterative development loops may be repeated as needed though at least once and can be approached using different methodological lenses.

integration (Schubatzky et al., 2025; Tondeur et al., 2012, 2025).

However, despite these well-established frameworks and their empirical implementations, practical challenges persist. Pre-service teachers report feeling overwhelmed by the time commitment required for technology-rich lesson design, often questioning their own capabilities, as the theory-practice gap perseveres (Henne et al., 2022; Priemer & Roth, 2020; Weiler et al., 2023). These recurring hurdles suggest that the existing frameworks, while theoretically comprehensive, have not yet fully addressed the practical dynamics that arise when pre-service teachers engage in authentic, technology-rich design tasks under self-regulated conditions. Taken together, these challenges point to one core issue: the possibility of an imbalance in the allocation of attention between technical demands and pedagogical reasoning in the digital learning design process.

To address these hurdles, we need to understand where pre-service teachers actually allocate their cognitive resources during the subject-specific design process. Specifically, there is little research explaining how prospective physics teachers distribute their attention between technical troubleshooting and pedagogical reasoning when designing learning environments with digital and maker technologies. This empirical gap is critical: without understanding where cognitive resources are being spent, teacher education programs cannot design scaffolding that effectively redirects attention toward pedagogical considerations.

This study addresses this gap through a design-based research (DBR) approach, where this work is the pilot-study of, conducted within the "Digi-Space" learning laboratory seminar at Leipzig University. As a discipline with particular practical relevance and proximity to real-world applications, subject-specific didactics requires approaches that allow practice and theory to learn from and benefit from each other (Berliner, 2002; Oh & Reeves, 2010; Prediger et al., 2015; Schmiedebach & Claas, 2021). DBR is the most common approach to fulfill this claim, adhering to characteristics such as sequential cycles of design, evaluation, and redesign as shown in **Figure 1** (Barab & Squire, 2004; Brown, 1992; Cobb et al., 2003; Edelson, 2002; The Design-Based Research Collective, 2003), real educational contexts (Dolmans & Tigelaar, 2012), and close interactions between researchers and practitioners (Platte et al., 2024; Veith et al., 2022).

The approach is particularly suited for coursework with content as fluid as the integration of digital media, where interventions must remain variable and adaptable while contributing to both practical design principles and theoretical refinement (Anderson & Shattuck, 2012; Haagen-Schützenhöfer & Hopf, 2020). This first iteration of the DBR cycle focuses on piloting and evaluating the seminar concept through qualitative measures of affective and process-related learner characteristics. Using weekly learning diaries and semi-structured interviews, we investigate how pre-service physics teachers distribute their time and cognitive focus among technical, content-related, and pedagogical aspects during the planning of digitally enriched lessons, and which factors most strongly shape their resource allocation. This study provides insights on how pre-service physics teachers allocate cognitive resources between technical troubleshooting and pedagogical reasoning during maker-based digital lesson design, revealing a systematic displacement of pedagogical reasoning by technical problem-solving. Based on this rationale, we address the following research questions (RQs):

RQ1: How do pre-service teachers allocate time and attention to technical, content, and pedagogical aspects during digitally enriched lesson design, and how does this allocation evolve over the seminar?

RQ2: Which mechanisms influence the teachers' time allocation and resource utilization most dominantly from their own perspective?

DEVELOPMENT

Design Desiderata

The design of the seminar is guided by general pedagogical principles that synthesize empirical findings on pre-service teachers' learning needs with established theoretical frameworks in science education and learning psychology. Task formats, roles, and reflection prompts are derived from documented learner needs rather than from a purely content-driven curriculum (Priemer & Roth, 2020; Rehfeldt et al., 2020). Learners are positioned as active participants throughout design, enactment, observation, and feedback cycles, ensuring that agency, diagnosis, and adaptive support are integral to the learning process (Priemer & Roth, 2020; Rehfeldt et al., 2020). Beliefs about digital media are addressed to promote strategy and concept enhancement with a focus on TPACK rather than school physics concepts, aligning conceptual growth with the seminar's disciplinary intent. Growth in specific TPACK knowledge areas is supported through learning laboratory activities (Lhotzky, 2023; Henne et al., 2022; Mishra & Koehler, 2006). Learning trajectories are sequenced from subjective experiences to abstract principles and back into situated applications, creating a coherent loop that supports sense-making and transfer (Priemer & Roth, 2020). Activities are embedded in socially rich realistic contexts (e.g., lesson simulations and enactments with genuine constraints) to maintain motivation and authenticity (Priemer & Roth, 2020; Rehfeldt et al., 2020). Concept development is scaffolded by multiple modalities (e.g., simulations, narrated explanations, and sensor-based data), informed by the Cognitive Theory of Multimedia Learning and cognitive load perspectives (segmentation, signaling, modality principles) (Chandler & Sweller, 1991; R. E. Mayer, 2009; Schnotz & Kürschner, 2007). The content architecture prioritizes learners' needs and self-directed focus areas over discipline-internal taxonomies; materials are openly accessible to support choice and depth, with hands-on media integration placed before the selection of any specific physics context (Becker et al., 2020; von Kotzebue et al., 2021). The following domain-specific desiderata operationalize these general commitments within the DiKoLAN competency architecture and the science-specific affordances of digital tools (von Kotzebue et al., 2021). The DiKoLAN framework functions as the reference backbone for planning, enactment, and evaluation; the DiKoLAN-Grid provides structured self-assessment and reflection on competency development, ensuring subject-specific operationalization and continuity with a national competence system (Becker et al., 2020; Meier et al., 2020; von Kotzebue et al., 2021). Multimedia design principles guide the construction of learning materials and tasks, while self-efficacy is targeted through mastery experiences, social persuasion, and reflection to influence motivation and subsequent technology use (Henne et al., 2022; R. E. Mayer, 2009). The seminar offers learning opportunities across all subtopics of digital media use in physics education while allowing students to specialize via iterative cycles of planning, enactment, and analysis, with targeted feedback to strengthen perceived ease of integration and self-efficacy (Henne et al., 2022). Active creation of digital artefacts (e.g., simulations and explainer videos) is prioritized over passive consumption, supported by worked examples and guided help. Structured reflection on usefulness and feasibility consolidates perceived value and prepares transfer to real classrooms. Studies document that when pre-service teachers actively design and reflect on digital media, their perceived usefulness and willingness to integrate such tools increase substantially (Lhotzky, 2023; Henne et al., 2022; von Kotzebue et al., 2021). Maker technologies (e.g., Arduino, sensors, 3D printing, and microcontrollers) complement classical digital media to afford authentic applications that bridge technological competence with experimental practice in physics (Henne et al., 2022; Lhotzky, 2023).

TPACK integration is both test-based and reflective, coordinating disciplinary, pedagogical, and technological knowledge (TK) through design rationales, diagnostic tasks, and evidence-based reflection to make knowledge interplay explicit and actionable (Henne et al., 2022; Mishra & Koehler, 2006). Professionally proximal experiences (e.g., lesson simulations and micro-teachings) are coupled with structured reflection to cultivate intention to use in future practice (Henne et al., 2022; Priemer & Roth, 2020). The SQD2 model is implemented via collaborative planning, peer feedback, and mentoring, emphasizing digital identity, instructional design models, and affective dimensions to institutionalize socially supported self-efficacy experiences and shared reflection on technology integration (Tondeur et al., 2025). Self-efficacy gains are engineered through successful enactments, targeted feedback, and peer resonance; meta-reflective formats and portfolios render development visible and inform realistic judgments about when and why digital tools are pedagogically warranted (Henne et al., 2022; Schubatzky et al., 2025).

Course Description

The seminar aims to enable pre-service physics teachers to integrate digital media into their teaching in a reflective and didactically sound manner. The structure follows an iterative, practice-oriented design cycling through theory, practice, and feedback for both presentations and teaching designs. An overview of the seven-session seminar structure is shown in **Figure 2**.

The seminar begins with a kick-off session in which instructors present the available digital media and maker technologies through worked examples. Working

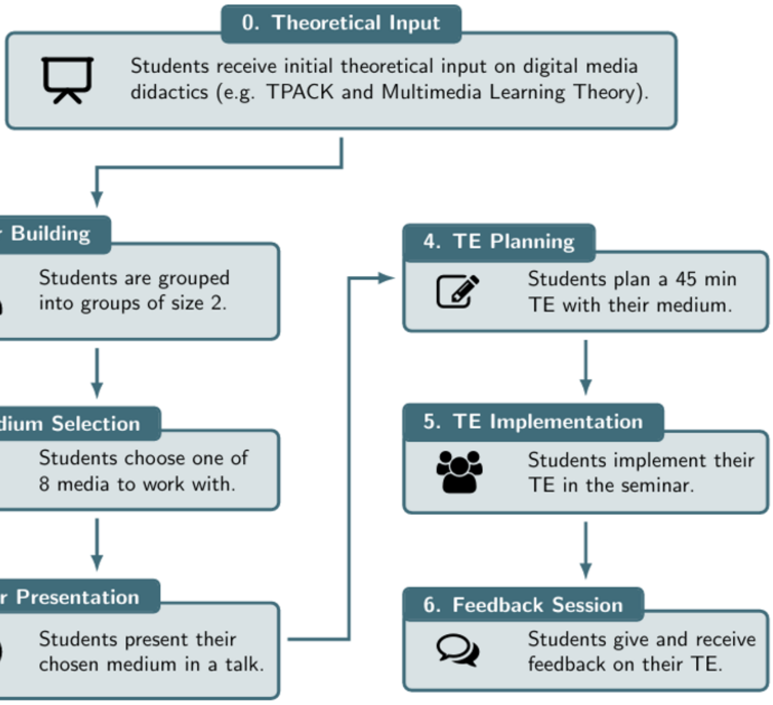

Figure 2. Overview of the seminar structure (the authors' own elaboration)

in pairs, students select their preferred medium and are assigned to groups based on these preferences. A theoretical foundations session then introduces key media-didactic frameworks, including cognitive load theory, multimedia learning theory, and the TPACK and SAMR models, supplemented by empirical findings on media didactics in physics. In a subsequent self-study phase of approximately two weeks, students prepare short presentations (15 minutes) on their chosen medium, which are delivered to the group with structured peer feedback. The core of the seminar is a longer self-study phase in which student teams independently design a physics teaching unit that integrates the chosen medium in a didactically meaningful way. Students choose the content, grade level, and framework conditions, aiming to identify a topic for which the medium adds educational value. The developed teaching units are then enacted in the seminar, with fellow students taking on learner roles (partly supported by role cards to promote authenticity), accompanied by multi-perspective feedback from peers and instructors using structured feedback forms. The seminar concludes with a final reflection and evaluation session, followed by a portfolio submission that includes the developed teaching unit and a reflective discussion of the feedback received. Detailed session descriptions and materials are provided in Appendix A.

METHODS

Research Design and Sample

This study is situated within the first iteration of a DBR cycle and employs a qualitative case study design to investigate pre-service physics teachers' resource allocation during digitally enriched lesson planning. As the initial pilot implementation of an iterative development process, this iteration focuses on an in-depth exploration of the phenomena under investigation rather than on broad generalizability (Braun & Clarke, 2006).

The qualitative approach is appropriate for capturing the process, experiences, and dynamics of prospective teachers' attention allocation in a naturalistic seminar setting. The sample comprised all N = 16 pre-service physics teachers present in the seminar, all in their sixth semester. They were invited to participate on a voluntary basis and informed that declining would have no consequences for their participation in or completion of the seminar. At the time of the study, participants completed foundational coursework in physics education, providing them with basic pedagogical content knowledge, as well as several courses in experimental and theoretical physics. However, no formal coursework on digital or educational technologies was part of their curriculum. Of these, N = 8 participants (one representative from each student pair) also completed guided interviews. Prior to the seminar, participants' prior experience with digital media in physics education and their motivation to engage with each topic were assessed using a pre-survey.

A post-survey was administered at the end of the seminar accordingly. These surveys served as a descriptive baseline for characterizing the sample and contextualizing the qualitative findings. They are reported for descriptive purposes only.

Data Collection

Two complementary qualitative data sources were used.

Learning diaries

During the planning phase of the teaching experiment (TE) (cf. **Figure 2**), students completed weekly learning diary entries via the online course platform over a six-week period. Each entry was structured around three predefined categories reflecting the TPACK model—technical, content-related, and pedagogical aspects. For each category, students described the extent to which it featured in their planning process and how much time they had spent on related activities or problem-solving. It is important to note that these categories do not constitute a measurement of the corresponding TPACK knowledge domains in the usual sense of the model. Rather, they served as a heuristic structure for documenting how students allocated their time and attention during lesson planning. The time estimates provided by students are numeric in nature but do not constitute scaled quantitative measures; they are treated as qualitative self-reports within the thematic analysis (TA).

Semi-structured interviews

To gain further insight into the mechanisms underlying time allocation, N = 8 guided interviews following Dresing and Pehl (2018) were conducted, with one representative from each student pair interviewed. The interview guide was developed based on the SQD2 framework and covered the following main topic blocks:

(a) experiences with digital media,

(b) authenticity and practice orientation,

(c) feedback and exchange culture,

(d) role of instructors,

(e) media use at institutional level,

(f) personal learning experiences and attitudes,

(g) assessment of seminar components, and

(h) open reflection.

All interviews were transcribed verbatim.

Data Analysis

The qualitative data were analyzed using reflexive TA following the six-phase framework proposed by Braun and Clarke (2006), supplemented by the recommendations of Ahmed et al. (2025). The analytical procedure comprised six iterative phases:

(1) familiarization with the data,

(2) generation of initial codes,

(3) searching for candidate themes,

(4) reviewing and refining these themes,

(5) defining and naming the final themes, and

(6) writing up the analysis.

Although presented as a sequence, the process was not strictly linear; rather, individual steps were revisited where necessary in order to improve the coherence, distinctiveness, and interpretive fit of the themes (Ahmed et al., 2025; Braun & Clarke, 2006). Initial codes were generated inductively from the data by the first author, while the third author independently coded a sample of the material; the resulting codes, candidate themes, and their interpretations were compared and discussed with the full author team, which contributed to their refinement and final naming. These discussions also served as peer debriefing by creating opportunities to explore alternative interpretations and challenge interpretive assumptions. As this study represents a pilot implementation within the DBR cycle, a more comprehensive coding procedure involving multiple independent coders and formal intercoder agreement measures is planned for subsequent iterations.

Trustworthiness

Several measures were taken to ensure the trustworthiness of the findings. Peer debriefing was conducted throughout the analytic process: an external co-author reviewed the coding process and confirmed the coherence of the thematic structure, providing an independent perspective on the analytical decisions (Lincoln & Guba, 1985). The use of a structured learning diary with predefined categories ensured systematic data collection across participants and time points. Furthermore, the triangulation of two complementary data sources (learning diaries and interviews) strengthened the robustness of the findings by allowing cross-validation of observed patterns. We acknowledge that certain trustworthiness measures commonly recommended for qualitative research, such as member checking, a formal audit trail, and a reflexive journal, were not implemented in this pilot study. While these measures were not feasible within the scope of this initial pilot implementation, they will be acknowledged for subsequent DBR iterations to further strengthen methodological rigor.

Ethical Considerations

Participation in this study was voluntary. All participants provided informed consent prior to data collection. Anonymization was ensured throughout the research process: all personal identifiers were removed from transcripts and diary entries, and participants are referred to by numbered labels in all reported data. Data protection was maintained in accordance with the institutional guidelines of Leipzig University. All standard ethical precautions for research involving human participants were observed.

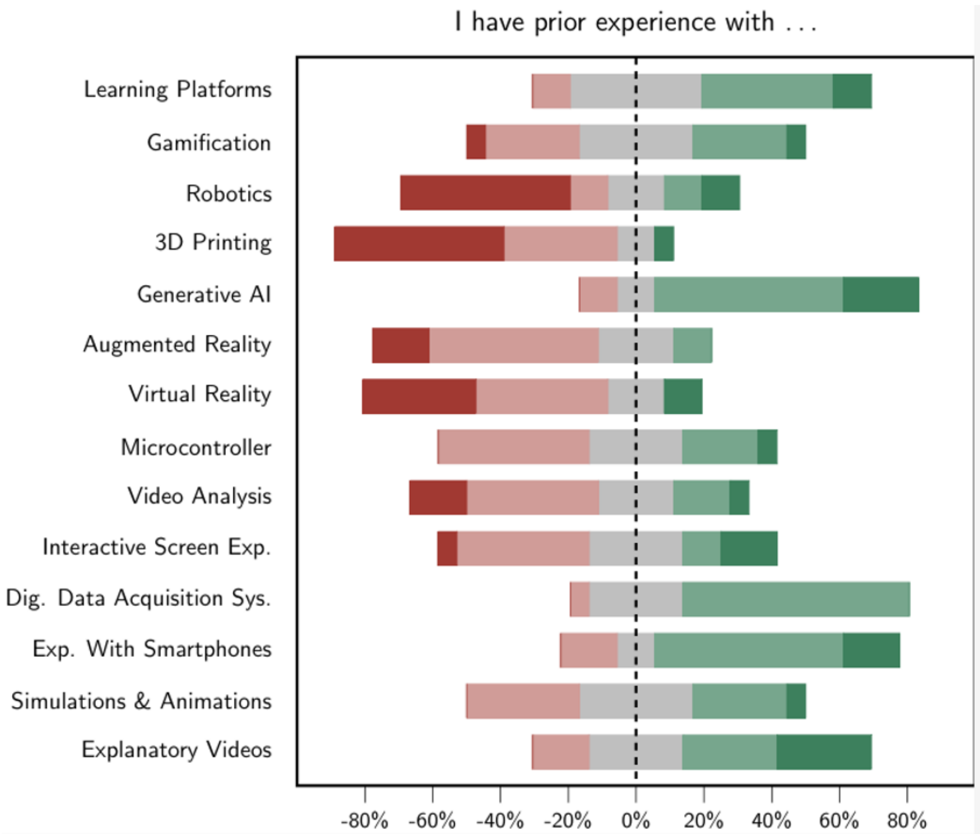

Figure 3. Students' prior experience with individual clusters of digital media education in physics lessons. Answers were given on a five-point rating scale (1: Strongly disagree, 2: Disagree, 3: Neutral, 4: Agree, 5: Strongly agree). (the authors' own elaboration)

RESULTS

First, the baseline data from the pre-post scales are presented, followed by a detailed presentation of the results for each RQ, respectively. In addition, the interview results are collectively summarized in tabular form in **Appendix A**.

The students report having some previous experience with most of the digital media mentioned: However, this experience is rather general in nature and therefore tends to be described as "rather little previous experience," as shown by the mostly central frequencies in **Figure 3**. There are a few exceptions: robotics, mixed reality (AR and VR), and 3D printing seem to have been little encountered by students so far, whereas they report a lot of previous experience with explanatory videos, learning platforms, working with smartphones, and, above all, generative AI.

Concerning the students' "interest" in the use of digital media for physics education, as a baseline there can be stated that the students started with overall medium to high curiosity for the topics. For some lesser-known topics like "microcontroller" or "augmented reality" the answers were more widely scattered as shown in **Figure 4**. However, only small differences can be observed between the individual categories. Given the small number of participants (N = 16), these variations are likely related to individual preferences. This curiosity or motivation to interact with each topic did not show any substantial changes: In the post-test, the scale showed additional motivation to engage with the topic for some topics such as "generative AI", others were somewhat more scattered after the seminar. Across all topics, however, "interest in topic XY" did not change significantly over the course of this seminar.

Results Regarding RQ1

Whilst in their independent self-study phase, the students had to answer questions regarding their progress and time allocation for each week. As described in the methodical outline, each preparatory activity can be assigned to one of the areas of the TPACK model. Shown in **Figure 5** is an overview of this time-allocation: The graph shows the progression of time spent, how much time was used in total per week, and how the proportions changed over time. The x-axis denotes the six weeks of independent study time to prepare the TE. In combination with the right vertical axis, this results in a diagram that describes the weekly working hours over the six weeks in the dashed line. Across weeks 1 to 5, the total time spent on preparation remains relatively stable at approximately three to four hours per week. In week 6, however, the total time drops markedly to about one hour on average. The percentages shown on the left vertical axis represent the proportional distribution of activity areas within each week's total preparation time.

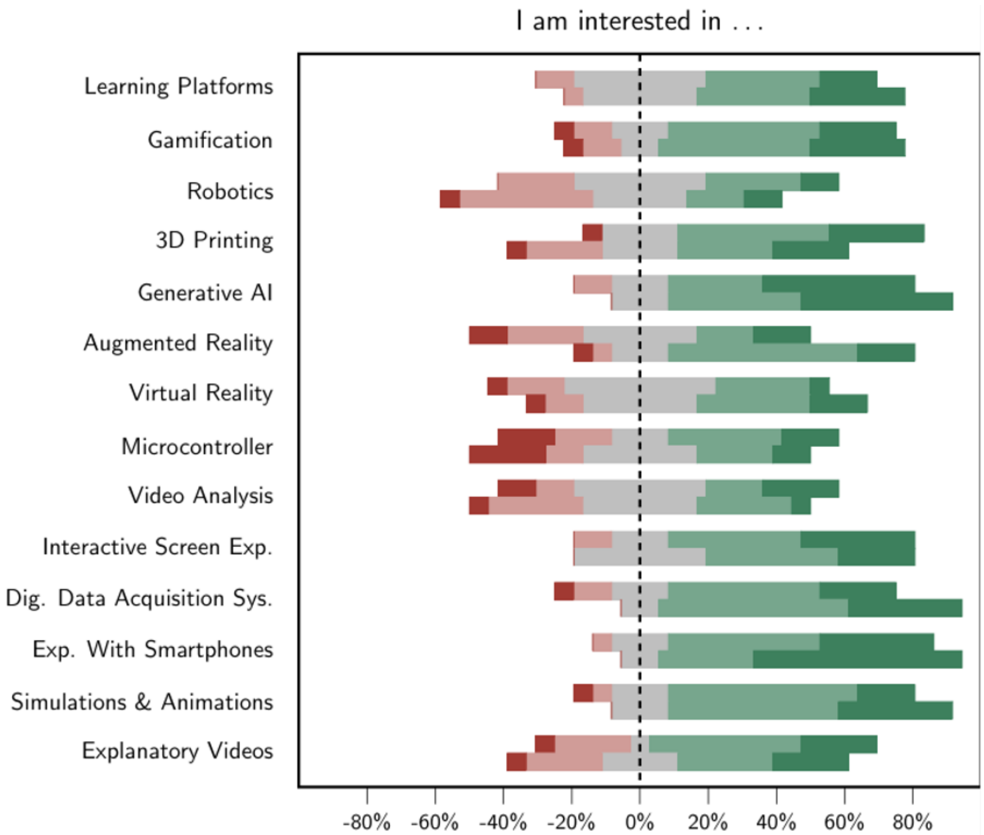

Figure 4. Pre-test (above) and post-test (below) on scale to indicate students' interest to engage in a topic of digital media for physics education (Weiler et al., 2024). Answers were given on a five-point rating scale (1: Strongly disagree, 2: Disagree, 3: Neutral, 4: Agree, 5: Strongly agree).

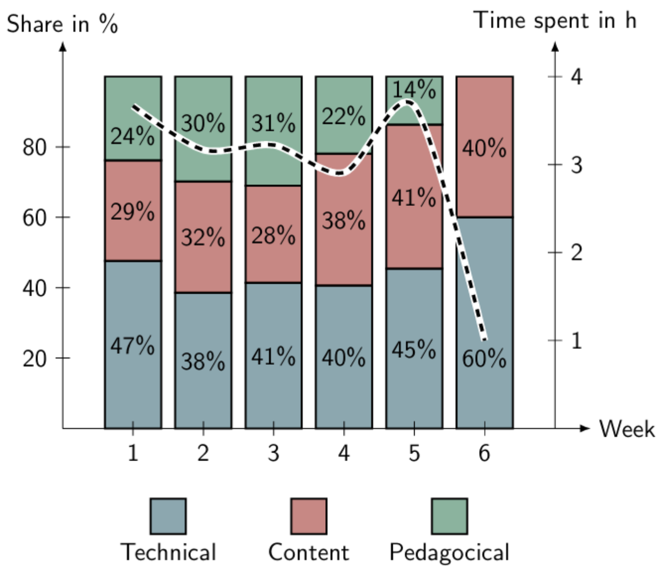

Figure 5. Information obtained from the learning diaries during the 6-week self-study phase, which is indicated on the x-axis (The right vertical axis corresponds to the dotted line and shows the total time the students spent on preparation during that week; The left vertical axis corresponds to the bar chart and shows the percentage of their total time that students spent on each of the activity areas (the authors' own elaboration)

This distribution indicates a decline in pedagogical activities over the course of the seminar, whereas content-related and technical activities remain comparatively balanced.

In week 1, for instance, around 50% of the total preparation time (approximately 2 hours) is allocated to technical activities, while content-related and pedagogical activities each account for about 25% (approximately 1 hour).

In the final week, the remaining preparation time is distributed evenly between technical and content-related activities, with no time allocated to pedagogical aspects. Together, these patterns indicate that pedagogical activities declined over the course of the seminar, with no pedagogical activity reported in the learning diaries for the final week, whereas technical and content-related activities continued until implementation. This does not necessarily imply that pedagogical design has been completed as a result of the students' planning behavior. Rather, the seminar structure required the teaching plans to be finalized approximately two weeks before the TE for quality assurance purposes, so that the last week was reserved primarily for revision, refinement, and technical or content-related finalization. One can infer, however, that the main structuring of the teaching sequences was completed around that time frame, details notwithstanding.

Table 1. Main themes derived from thematic analysis of the interviews

Theme	Description	Anchor item
Technical novelty	Technical difficulties that hindered the learning process, stemming from new material involving previously unfamiliar hardware and software or a lack of developed technical skills (e.g., coding).	"I spent four hours trying to figure out how to do it. I googled it a few times, but I couldn't find it. That took away my motivation because I just didn't know how to adjust the model correctly." (Participant 07)
Reluctance to approach lecturers	Despite open doors, many found it difficult to actively seek help. Reasons: shame, perfectionism, desire for autonomy, student culture.	"So, on my own, it goes something like this [....] And so the last step, I think, is always to go to the instructor, at least for me." (Participant 04)
Varied structure in self-organization	Topics such as division of labor, time management, workload management, and self-discipline. Some groups were very structured, while others worked "at the last minute."	"We rarely met in person but organized a lot via WhatsApp and phone calls. We assigned ourselves tasks to complete, and that worked quite well for us. [...] At the same time, I have to say that we are both the type of people who tend to do everything at the last minute." (Participant 08)
Unclear requirements	Recurring theme: Uncertainty about the depth of expectations and requirements for teaching units or products.	"We understood that we had to do something completely new. [...] We didn't even know what 'new' meant. As a result, we went in completely the wrong direction at the beginning." (Participant 07)

Note. The categories describe possible causes of changes over time and in resource use based on the students' own statements

When asked, the students themselves responded that their time spent on the seminar work generally cumulated towards their TE. In combination with the free-form answers of the learning diaries an overall trend can be observed. Within the TE-planning phase, students typically took the following progression: First they spend most of their time familiarizing themselves with the new technology, then the focus shifts slightly in favor of didactical and pedagogical considerations. With time content considerations, in particular, reviewing the physics and, as a result, developing specific educational content-specific materials, are becoming more prominent. Roughly two weeks before the actual TEs time-allocation peaks and the week directly before the lesson is mostly reserved for technical- and content-wise finalization with a total spent time of ca. an hour overall.

Results Regarding RQ2

The TA of the interviews revealed a hierarchical pattern of barriers that collectively redirected cognitive resources from pedagogical design toward operational problem-solving.

First-order barrier: Technical novelty

The most frequently reported factor was technical novelty as described in **Table 1**, which operated at multiple levels. Students described being overwhelmed by the sheer number of available tools and resources: "because when you google it, you feel completely overwhelmed because there are so many options" (participant 02). Beyond initial orientation, technical difficulties with unfamiliar hardware and software further consumed time and cognitive resources. The VR/AR group, for instance, reported spending considerable effort on basic operational questions such as "just to understand [...] how am I supposed to walk around in there now that I'm wearing these glasses?" (participant 04). More fundamentally, shortcomings in technical skills such as programming substantially hindered the development process, causing students to lose focus and motivation: "I spent four hours trying to figure out how to do it. I googled it a few times, but I couldn't find it. That took away my motivation because I just didn't know how to adjust the model correctly" (participant 07).

Second-order barrier: Self-regulation deficits

The pressure created by technical novelty was amplified by heterogeneous self-regulation strategies. Some groups were highly structured, while others deferred most work until shortly before the deadline:

> "But it's not necessarily just about the module; it's also simply part of the overall picture. The fact that we're taking a completely different subject at the same time, just like other physics modules that also demand our attention. So it just got pushed back a bit and ended up piling up a little more toward the end" (participant 01).

At the same time, the responses suggest deficits in self-regulation that extended beyond the seminar itself and became visible in students' broader handling of competing academic demands across courses.

Third-order barriers: Unclear requirements and reluctance to seek help

Two additional factors prevented students from redirecting their attention back toward pedagogical design. First, uncertainty about the depth of expectations led to unfocused effort: "We understood that we had to do something completely new. [...] We didn't even know what 'new' meant. As a result, we went in completely the wrong direction at the beginning" (participant 07). Second, despite the professorship's open-door policy, students were reluctant to approach instructors. "And when we then fail at simple things, things that seem simple to us, it makes us think, consciously or subconsciously, 'No, I can't ask about that'" (participant 07). As a result, students reported that at the beginning of the self-study phase they did not know how to handle the amount of freedom. Taken together, these four barriers formed a self-reinforcing pattern: technical novelty consumed the majority of available time and cognitive resources, while self-regulation deficits compressed the remaining time further, and unclear requirements combined with reluctance to seek help prevented students from accessing the support structures that might have helped them redirect attention toward pedagogical design. More specifically, the interview accounts suggest that technical novelty generated additional troubleshooting demands, while unclear task requirements increased uncertainty and reluctance to seek help appeared to prolong problem-solving in the context of limited time and uneven self-regulation. Under these conditions, operational problem-solving effectively displaced pedagogical reasoning as the dominant focus of student activity.

DISCUSSION

Interpretation of Findings

First, the findings extend research on teacher readiness in digital pedagogy by showing that technological mastery does not automatically lead to pedagogical integration. In this seminar, technical engagement often became a competing demand for attention, time, and self-regulation, so readiness must be understood not only as willingness or confidence, but also as the capacity to keep pedagogical reasoning in view while technical problems are being solved. This interpretation is consistent with prior work showing that integrated technological and pedagogical support can increase combined design justifications but does not necessarily improve the quality of lesson plans, and that pre-training or more sustained support may be needed to make such support effective (Hessen et al., 2026; Janssen et al., 2019). More broadly, it aligns with reviews of teacher professional development emphasizing collaborative, hands-on, and mentored support rather than isolated exposure to digital tools (Amemasor et al., 2025; Enochsson & Rizza, 2009). Regarding the stagnant descriptive interest values: The lack of change in interest in individual media can be explained quite plausibly in light of expectancy-value theory (EVT) (Wigfield & Eccles, 2000). EVT distinguishes not only between positive value components but also explicitly between the perceived costs of a behavior, such as additional time, effort, or cognitive load (Flake et al., 2015). In the context of this seminar, this means that an in-depth engagement with digital media can reveal not only their potential benefits or appeal, but also the actual labor intensity, complexity, and additional effort associated with their use (Chan & Zhou, 2023). From the perspective of EVT, in-depth work with digital media can lead to greater visibility not only of their potential value but also of their perceived costs, such as additional time, greater complexity, or a heavier workload. In practical terms, this means that as users become more familiar with a particular medium, their initial assessment of working with it is adjusted—without this necessarily resulting in an increase in interest. Furthermore, the four-phase model of interest development also supports a more media- and topic-specific interpretation. Hidi and Renninger (2006) describe interest as a process that progresses from triggered situational interest, through stabilized situational interest, to a more individualized, deeply rooted interest. It follows that interest in one medium does not automatically transfer to other digital media but rather remains tied to specific content and experiences in each case. This finding is consistent with the findings of the DiKoLeP study. There, too, the results showed positive motivational and affective developments—particularly regarding the motivation to use digital media in future lessons—but at the same time, self-efficacy expectations did not increase significantly (Weiler et al., 2024). The authors attribute this, among other things, to the fact that the participants already had very high self-efficacy scores at the outset, and that the practical learning opportunities, particularly hands-on phases and microteaching with feedback, may have led to a more reflective and realistic self-assessment. This same mechanism applies to interest: Here, too, practical work with the media may initially result not so much in a linear increase as in a correction of initial expectations, because students realize that working with a medium requires more and different kinds of effort than they had initially assumed. Overall, students demonstrate a progression throughout the development process that initially focuses heavily on the technical aspects and only subsequently follows the typical path of didactic preparation: first, subject-matter and conceptual clarification; then, didactic and pedagogical considerations; and finally, the selection and implementation of methods. This pattern is consistent with the seminar's focus on the use of the aforementioned media and maker technologies themselves. Building on the TPACK framework by Mishra and Koehler (2006), our findings suggest that, under conditions of high technical novelty, unstable technological competence can constrain opportunities for pedagogical-technological integration. In such situations, technical problem-solving may compete with pedagogical reasoning for limited time and cognitive resources, making integrated knowledge work more difficult without implying a fixed developmental sequence in which TK must be fully developed first. Prior work on the close interweaving of theory and practice supports this interpretation, as an initial focus on technology can be considered desirable when it supports the learning process itself, particularly with regard to motivation and affect (Große-Heilmann et al., 2022; Tondeur et al., 2012, 2025), as reflected in statements such as "I think what was actually useful in practice was conducting the experiments, the fact that you actually learn something from them. [...] I think it's really cool, simply because it's motivating ..." (participant 05). Various underlying processes guide how time is allocated. Among these, "technical novelty" particularly emerged with a broad scope: ranging from initial overwhelm due to the vast array of online resources to a lack of technical hard skills such as coding, technical novelty appeared to have the strongest influence on all subsequent decisions and inhibitions. This once again reflects, in particular, the initial learning process in the field of technical knowledge. According to the students, this is attributable, on the one hand, to the desire not to hit a wall (cf. participants 07, 04, 01) and, in relation to this, the relatively late emergence of a sense of self-efficacy. This is consistent with the findings of Schubatzky et al. (2025) as well as earlier works (Große-Heilmann et al., 2022; P. Mayer & Girwidz, 2019; Tondeur et al., 2020): If early stages of seminars or independent study are primarily experienced as a laborious technical challenge, this can delay the development of self-efficacy, and as a result, the sense of usefulness and ease of integration develop later and to a lesser extent (Joo et al., 2018; P. Mayer & Girwidz, 2019, cf.). On the other hand, the students also stated that they had made little to no use of the materials provided for orientation. Technical novelty can be interpreted in multiple dimensions in this case: In terms of orientation novelty (Where do I start?), and in operational novelty (How do I work with this?). Then also in productive novelty (How do I use this to create a viable teaching product?) and last, didactic novelty (In what way is this didactically meaningful?). While the original design already provided explicit support for orientation and didactic novelty, implementation revealed remaining challenges particularly in relation to operational and productive novelty. These challenges may have been reinforced by study conditions shaped by e-learning structures common at many universities, in which extended self-study phases are either uncommon or largely confined to exam preparation, whereas most teaching is organized through more traditional classroom-based formats (Kerres, 2012, 2022). In this context, operational and productive novelty confronted students with collaborative and self-regulated forms of work that were not yet fully routinized. As a consequence, cognitive resources appear to have been directed not only toward the design task itself, but also toward self-regulation and group coordination (Järvelä & Hadwin, 2013; Sweller et al., 2011). This interpretation is consistent with the additional factors reported by students, including reluctance to seek support from lecturers and pronounced differences in self-organization and structuring strategies. A similar pattern is visible in the limited use of peer presentations as a resource for lesson planning. Instead, greater emphasis was placed on the productive demands of developing one's own materials. In combination with the generally low use of the provided materials, this may help explain the uncertainty students expressed regarding the didactic scope and appropriate application of digital media in physics instruction. Such uncertainty is also compatible with the slight tendency toward the midpoint in the post-test measure of interest. Under these conditions, attention appears to have shifted primarily toward the effort, scope, and feasibility of individual media rather than toward their didactic potential. Experiences from the learner perspective during peers' TEs then seem to have contributed to a more differentiated view of these media. This may account both for reduced apprehension and for a more restrained assessment of their relevance, indicating a shift from initial novelty-driven expectations toward a more realistic appraisal (Clark, 1983; Weiler et al., 2024). In summary, an initial concentration on technological aspects appears plausible in this seminar format. It becomes critical, however, when it delays or limits pedagogical reflection. This risk was particularly evident where technological novelty coincided with open task requirements. Taken together, the interview data suggest a hierarchical pattern in which technical novelty consumed attention first, self-regulation compressed available time next, and unclear requirements together with reluctance to seek help prevented students from redirecting effort toward pedagogical design. In this seminar setting, operational problem-solving therefore displaced pedagogical reasoning when scaffolding was not sufficiently visible or binding. This risk was particularly evident where technological novelty coincided with open task requirements. Therefore, the question also arises as to why the students did not choose or even notice the scaffolded materials as a starting point. Feedback and information from the individual contributions provide clues as to the causes: For one thing, the high density of information in the first live sessions suggests that references to the provided scaffolds were lost amid the abundance of content-related and organizational details. On the other hand, a lack of commitment and explicit accountability appears to have led students to resort to familiar strategies, such as free web searches, that are less efficient in the context of complex material searches.

Within the framework of the SQD model it is emphasized that scaffolding must not merely be offered as a purely passive resource but must be framed by active modeling and social support. As a result, for the next iteration of DBR, the seminar design will be refined to include two mandatory live sessions: one at the beginning of the seminar for initial orientation and another immediately before the TE takes place.

This approach aims to increase commitment and ensure that the curated materials are recognized and used as the primary resource at the crucial stage of lesson planning. The findings thus point to several implications for future iterations of the design.

Implication for Redesign

The redesign implications point to one central balancing problem: autonomy is valuable, but it must be organized so that it does not allow technical novelty to monopolize attention at the expense of pedagogical reasoning:

As previously discussed, an initial focus on technology is to be expected in a seminar that introduces new media and maker technologies. This only becomes problematic when it permanently supplants theory-based lesson planning, since while lesson planning is considered a central professional requirement, its relationship to professional knowledge has not yet been conclusively clarified empirically (Krauss et al., 2008; Loughran et al., 2006). Especially for physics, studies show that subject-specific didactic and pedagogical knowledge in particular promote the development of planning skills (Große-Heilmann et al., 2022; Riese & Reinhold, 2010; Schubatzky et al., 2025). Thus the early focus on technology must be framed didactically in such a way that it is translated into planning guided by subject-specific didactics and pedagogy.

While the dimensions of orientation and didactic novelty were already explicitly addressed in the original design, gaps emerged during implementation particularly in the areas of operational and productive novelty. These gaps can, at the institutional level, be mapped onto the SQD2 criteria of “modeling,” “collaboration,” and “feedback,” from which the following redesign implications derive: The technical overload and unclear starting point highlight a need for more modeling and structured support, for example in the form of a longer, more intensive selection phase for the chosen media in order to model their use (Lhotzky, 2023). The limited use of materials and presentations calls for better alignment of theory and practice. This could be addressed through the previously mentioned gradual introduction to self-study phases, with instructors more actively modeling the use of materials. The reluctance to approach instructors shows the need for a lower-barrier feedback architecture, where different types of feedback loops and increased support can offer solutions (Bauer et al., 2025; Tondeur et al., 2025; Weiler et al., 2024).

Heterogeneous self-organization, finally, points to the need for more structured collaborative design phases. The goal here is not simply to increase the amount of pre-structured schooling, but rather to provide timely support at the outset so that autonomy can actually become productive later on. Explicitly designated seminar sessions could preserve open-ended work while using structured guidance to direct students toward the materials provided at the outset. Modeling and structured support in hard skills outside one’s area of expertise, such as coding, can take various forms. Even though block-based coding was already included (e.g., Scratch), further structured support could be integrated by giving pseudo-code examples in order to help students structure what they want their program to do. Another way would be to encourage and educate the students more proactively by using all the tools available to them, e.g., codify or vibe coding via the typical large language models. And thirdly pointing out the support given more actively in the mentoring, in order to more closely accompany their first steps, is a reasonable amendment to the current design.

The limited use of peer presentations for theory-based planning indicates that the current timing of these sessions tends to hinder the development of self-efficacy. Another concrete redesign proposal would therefore be to retain the original idea of peer learning by framing the presentations as worked examples and reflections on them: This creates an opportunity to learn from the hurdles experienced together by reflecting on them in the seminar, while still transferring the technical knowledge aspects to fellow students.

Overall, the findings do not suggest reducing authenticity, autonomy, or technology-focused design tasks. Rather, these elements require more deliberate scaffolding, particularly at the beginning of the seminar. In this pilot, high technical novelty combined with broad openness and comparatively weak initial guidance appears to have shifted attention toward operational problem-solving and away from theory-based lesson planning. Future iterations should therefore preserve students’ responsibility while sequencing it more deliberately through stronger early modeling, clearer entry points, and a feedback architecture that makes support visible when students begin to seek direction. This approach can help technological exploration become a productive starting point for subject-specific didactic and pedagogical reasoning instead of a competing demand.

Limitations and Outlook

The study has several limitations. First, the analysis focuses on process characteristics of lesson planning rather than on the quality of the resulting lesson plans or longer-term developments in self-efficacy and intention to use digital media. This focus is deliberate, as planning competence in physics instruction is complex and multifaceted and cannot be readily captured by isolated indicators (Meinhardt et al., 2018; Shulman, 1987; von Aufschnaiter et al., 2015; von Kotzebue et al., 2021). Future design cycles should therefore combine process-level observations with more nuanced assessments of planning quality, depth of reflection, and affective outcomes, for which the DiKoLAN framework offers a promising approach to operationalizing subject-specific competencies in a theory-oriented manner. Second, the numerical time estimates recorded in the learning diaries were self-reported descriptive information rather than validated quantitative measures. They indicate how participants reported allocating their time, but they do not constitute direct measures of cognitive attention or cognitive resource allocation and may be affected by estimation and recall biases. Third, the sample is small (N = 16) and drawn from a single pilot implementation of a seminar tailored to local conditions, which limits the generalizability of the findings. As is typical for DBR, the concept was closely adapted to a specific institutional and curricular context.

Based on these findings, the next iteration of the DBR cycle will incorporate several targeted changes: two mandatory live sessions to structure the initial orientation phase, revised scaffolding materials with clearer task expectations, and stronger instructor modeling during the entry phase to reduce the cognitive burden of self-regulated exploration. These planned modifications directly address the core finding that high technical novelty combined with open task structures can displace pedagogical reasoning.

More broadly, the findings inform the design of digital teacher education beyond physics-specific contexts. The observation that TK can function as a practical precondition for pedagogical integration suggests that teacher education programs introducing novel digital tools should not treat technical familiarization and pedagogical reasoning as parallel tracks but rather sequence them deliberately: ensuring sufficient technical stabilization before expecting integrated knowledge work. This principle applies whenever pre-service teachers encounter unfamiliar technologies under self-regulated conditions, regardless of subject domain or institutional setting. At the same time, the seminar’s high degree of autonomy and authentic design tasks was valued by participants and should not be reduced; the challenge lies in scaffolding these elements more effectively at the outset so that exploration becomes productive rather than overwhelming.

CONCLUSION

This study examined how pre-service physics teachers allocate time and cognitive resources during technology-rich lesson design, and which factors shape this allocation. Addressing **RQ1**, the learning diary data reveal a pronounced asymmetry in attention allocation: across the six-week self-study phase, students devoted the majority of their time to technical aspects, while reported pedagogical activity declined over time and was not recorded in the diary entries for the final preparation week. Addressing **RQ2**, TA of the interviews identifies four dominant mechanisms shaping this allocation: technical novelty, inconsistent self-organization, unclear task requirements, and a reluctance to seek instructor support. Notably, these factors do not appear to reflect a lack of motivation; rather, they indicate that high technical novelty combined with open task structures can systematically redirect cognitive resources away from pedagogical design toward operational problem-solving.

From a theoretical perspective, the results carry implications for how the TPACK framework (Mishra & Koehler, 2006) is operationalized in teacher education. The framework describes the interplay of technological, pedagogical, and content knowledge without specifying temporal or developmental dependencies between these domains. Our findings suggest, in line with the SQD2 model (Tondeur et al., 2025) and the DiKoLAN competency architecture (von Kotzebue et al., 2021), that sufficient TK may function as a practical precondition for the integrated knowledge processes TPACK describes: when TK remains unstable, technical problem-solving can overshadow pedagogical reasoning, potentially hindering the development of integrated TPACK. This raises the question of whether teacher education programs should deliberately stage the development of TK before expecting meaningful pedagogical-technological integration, rather than treating all knowledge domains as parallel and equally accessible from the outset.

More broadly, these findings suggest that technology integration in teacher education is not only a matter of mastering and integrating technological, pedagogical, and content knowledge, but also of how technical demands influence the allocation of time and attention during authentic learning design. If technical novelty is not addressed through adequate initial scaffolding, it risks displacing the very pedagogical reasoning that technology integration is meant to enhance. For program design, this implies that sequencing matters: ensuring sufficient foundation in technical knowledge, including procedural activities, before expecting integrated knowledge work may be a generalizable principle applicable across subject domains and institutional contexts. At the same time, the value of autonomy and authentic design tasks should not be diminished; rather, the challenge lies in scaffolding these elements more effectively at the outset. Future research should investigate whether staging TK development in structured phases leads to more balanced attention allocation and stronger TPACK outcomes, and how these dynamics play out across different disciplines, tool ecosystems, and cultural settings.

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APPENDIX A: DETAILED COURSE DESCRIPTION

Kick-Off Meeting – Introduction and Media Selection

The instructors first present the available digital media and maker technologies through worked examples and exemplary application scenarios, allowing students to experience concrete possible uses, particularly for media that are previously unfamiliar to them. Working in pairs, the media are assigned to each group based on their selected preferences. The accompanying online course offers structured access to all materials in the form of thematic tiles: introductory guides, subject-specific literature, sample files (such as Arduino scripts, VR scenarios), check-up questions and tips for lesson planning as shown in **Figure A1**. In addition, communication platforms (forum, Zoom link) and a tool for booking consultation hours are available.

Theoretical Foundations – Media Didactics and Subject-Specific Didactic Models

The second session is devoted to key theories of media didactics. In addition to cognitive load theory (Sweller et al., 2011) and multimedia learning theory (R. E. Mayer & Moreno, 2002), the TPACK and SAMR models are discussed. Empirical findings on media didactics in physics are presented to supplement the discussion. The aim is to lay a theoretical foundation for later lesson planning with digital media.

Independent Preparation Phase I – Development of Short Presentations

In an initial self-study phase (approximately two weeks), students develop short presentations (15 minutes) on their chosen medium. The presentations serve both as a technical discussion and as an introduction for the seminar group to the basic handling of the respective medium.

Presentation Sessions With Peer Feedback

The student teams present their short presentations to the entire class. This is followed by structured Q&A sessions with the group and brief feedback from the instructors. All presentation materials are available through the course platform.

Independent Preparation Phase II – Planning Digitally Enriched Teaching Units

The groups independently design a physics teaching unit in which the chosen medium is integrated in a beneficial way. The students choose the content, grade level, and framework conditions with the aim of identifying a topic for which the medium adds educational value. This reversal of the usual planning logic (starting with the method) enables a practical approach to the use of media. During the planning phase, the teaching and learning lab, technical resources, and individual support from the team of lecturers are available.

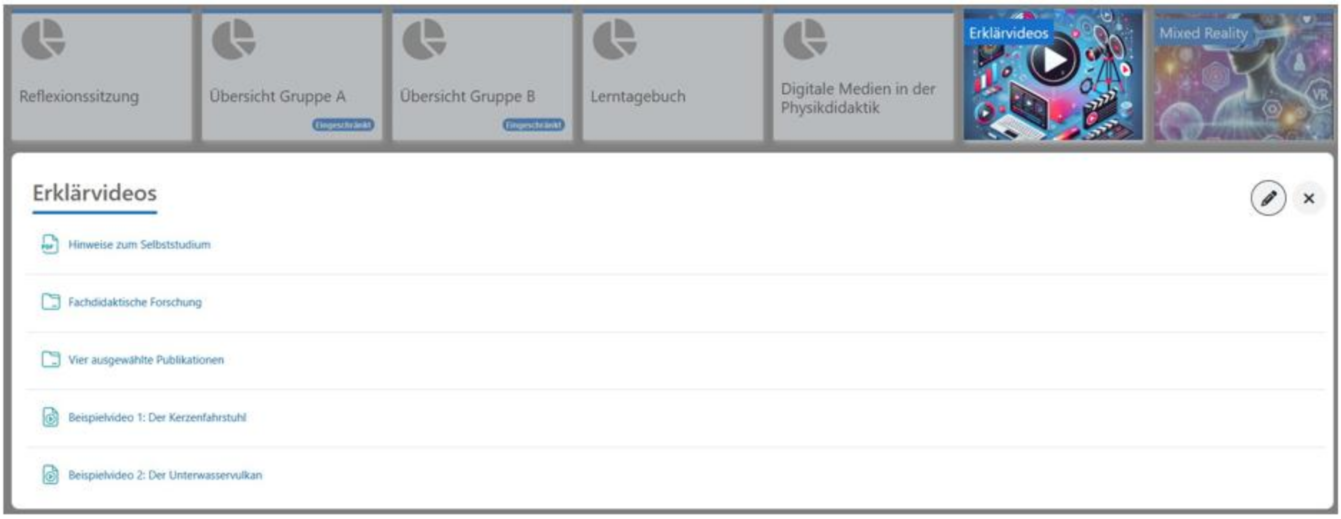
Teaching With Multi-Perspective Feedback

The developed teaching units are carried out in the seminar. The fellow students take on the role of learners, partly supported by role cards to promote authenticity. Each teaching unit is accompanied by two peers and both instructors using structured feedback forms. The aim is to encourage a practical, evaluative examination of one’s own teaching practices.

Final Reflection and Evaluation

In the final session, participants reflect on the course and content of the seminar in rotating small groups and via anonymous written feedback. Afterwards, the students submit a portfolio that includes the developed teaching unit as well as a reflective discussion of the feedback they received. An overview of the entire timeline of the seminar is illustrated in **Figure 2**.

(a)



(b)

Figure A1. A section of the online course: (a) The section displays the individual tiles, i.e., the available media and maker technologies and (b) The lower section shows an open tile using the example "explanatory videos." (As described, the content consists of instructions or guidance for self-study, related research, selected publications, and practical examples) (the authors' own elaboration)