

ARTICLE

Teacher Professional Development for Effective Incorporation of Augmented Reality Utilizing TPACK, Assessment as Learning, Pace Differentiation, and Dialogic Coaching

Ken Dong^{1,*}, Russell Hazard¹

¹ NIT Education, Beijing, China

*Corresponding author. Email: dongken@alumni.nmt.edu

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Abstract

This research explored a professional development program for high school teachers to support matching pedagogy to technology and content. The specific use case was the integration of augmented reality into classrooms to support differentiated instruction, coaching, and enhance student comprehension of abstract ideas. A qualitative approach was employed, combining classroom observations to gather data on teachers' experiences of using augmented reality with semi-structured interviews. The results indicated that while teachers saw great potential for augmented reality as an immersive and interactive learning medium, they also foresaw difficulties in aligning the technology with pedagogical and content objectives without support. Major conclusions drawn from the study highlight the importance of professional development that not only covers technological affordances, but also mentors' teachers in analyzing how various pedagogical approaches and technologies may interact with specific content knowledge. It was also noted that designing professional development in such a way as to allow teachers to experience learning in the role of students was effective for the learning goals. Finally, reflections regarding technology and the future of education included hopes for a more personalized learning experience and concern that factors like comparisons between students could have negative repercussions, especially as AR is enhanced with artificial intelligence. The significance of this research lies in its contribution to understanding the role of tailored professional development in equipping teachers to effectively incorporate emerging technologies into their teaching strategies, ultimately aiming to foster more dynamic and inclusive educational environments.

Keywords: Teacher Professional Development; Augmented Reality; TPACK; Differentiation; Coaching

1. INTRODUCTION

Professional development (PD) is a key factor in enhancing teaching quality and learning outcomes for students [33]. Effective PD enables educators to deepen their understanding of pedagogy [16] and supports their motivation, knowledge acquisition, and implementation of improved practices [44]. Rapid technological advancements continue to transform educational environments. However, technology does not ensure improved learning outcomes unless they are embedded within sound pedagogical strategies [2]. Both learning to teach with transformative technology and supporting students in learning with it is increasingly important as technologies such as generative artificial intelligence (AI) increasingly disrupt classrooms and workplaces [53]. Pedagogical frameworks integrating technology, such as TPACK [24] and SAMR [33], are widely recognized among researchers and professional development facilitators. However, faculty at all levels of education need to learn how to incorporate the affordances of technologies such as artificial intelligence or augmented/virtual reality with strategic pedagogical approaches that align with the content knowledge.

Both Augmented Reality (AR) and Virtual Reality (VR) are increasingly integrated across K–12 settings, higher education, and vocational training [48]. AR, in particular, has demonstrated positive impacts on student engagement and motivation [30]. By enabling immersive interactions with virtual

models and data, AR promotes active, experiential learning [31], making it especially valuable for exploring otherwise intangible concepts such as molecular structures, distant geographies, or abstract frameworks [48]. AR also presents challenges for faculty; its novelty and visual appeal may distract from learning objectives if not paired with sound instruction, and many educators lack confidence in designing lessons that leverage these technologies effectively [21].

In China, AR training from technology providers emphasizes device function over pedagogical application. Even when teachers possess technical competence with AR devices, uncertainty regarding optimal utilization may persist, particularly as it relates to specific content area and student needs. Consequently, there is a need for research on contextually appropriate and effective professional development for AR use [32]. The present study aims to examine the perspectives of high school teachers who are new to AR following their participation in an introductory PD workshop designed to model how technological affordances (engaging and interactive concretization of abstract ideas in AR environments) meet pedagogical approach (integration of AR into a wider Assessment as Learning workflow with pace differentiation and individual coaching) to help elucidate specific target content knowledge (literary analysis and mythological comparison using the Hero's Journey model [7]). As the target learning of the professional development was classroom practice informed by theory, and not just theory, this research examines how demonstrating an example of alignment between content, pedagogy, and technology by putting faculty in the role of students using the technology may also help create empathy and transfer.

2. LITERATURE REVIEW

Augmented Reality (AR) has emerged as a transformative tool in education, offering students immersive and interactive experiences for some applications and content. Conventional methods often struggle to sustain engagement, whereas AR can generate dynamic, engaging environments that foster creativity and maintain attention [3]. Research indicates that AR can enhance motivation, facilitate information visualization, and can improve interactive performance [18]. Systematic reviews have shown improvements in motivation, attention, understanding, performance, and knowledge retention through AR integration [35,48]. By providing rich visual and auditory content manipulable by learners, AR helps extend attention spans and reduce disengagement. Executed well, teaching with AR may also contribute to 21st century skill acquisition [49].

Studies by Lee et al. [26] demonstrate that VR/AR solutions may be superior to conventional methods for teaching procedural knowledge and visually complex content. These technologies also afford educators greater opportunities for coaching individuals while students work independently. Participation in AR simulations offers students safe, controlled practice to refine skills [26,54]. Well-crafted AR activities are conducive to fostering higher-order thinking and twenty-first-century competencies, including critical thinking, problem-solving, and creativity [5,10,41,49]. By allowing learners to apply theoretical knowledge and manipulate three-dimensional representations, AR facilitates deeper comprehension of complex subjects. This benefit is particularly pronounced in disciplines such as biology and chemistry, where students can observe hard to visualize molecular and chemical processes firsthand [19,36]. Sirakaya and Cakmak [47] further affirm that AR strengthens spatial abilities and conceptual understanding in STEM contexts. Salehi [39] notes that AR use for English language acquisition can be helpful as it also supports multimodal interaction and the anchoring of abstractions into concretized contexts. This resulted in improved learning outcomes for students.

Despite these advantages, practical and logistical challenges persist. Budgetary limitations frequently restrict the adoption of AR in educational institutions [22]. Technical limitations, such as insufficient model fidelity, inflexible applications, glitches, tracking errors, latency issues, and unfriendly interfaces can disrupt instruction and increase user frustration [9,27,43]. Reliable internet connectivity is also essential to support most AR resources. Moreover, the technical complexity associated with AR tools—including navigation, device manipulation, and curriculum integration—may intimidate and challenge both instructors and students [1,32].

Cognitive overload is another concern, as some students may find AR's interactive features overwhelming or distracting [1]. Garzón et al. [15] confirm that pedagogical design remains

fundamental for meaningful AR integration, regardless of approach—collaborative, inquiry-based, situated, or project-based learning. Empirical evidence underscores these challenges. Dunleavy et al. [14] describe how students, absorbed by AR tools, neglected critical components of inquiry-based activities, and Ibáñez et al. [20] report that one quarter of simulation tasks were left incomplete despite high motivation, resulting in lower than anticipated effectiveness. Trends in augmented reality (AR) usage in education reveal ongoing challenges in developing engaging and pedagogically sound experiences that correspond with curriculum objectives [4]. Jesionkowska et al. [22] identified institutional constraints such as lack of AR hardware, rigid courses and assessments, resource limitations for educators, and restricted timeframes as significant barriers to AR implementation. Achieving alignment with local learning requirements may necessitate considerable investment in personalized programs or upgraded hardware, and current AR technology lacks the artificial intelligence to improvisationally generate content adaptive to individual learning abilities. Chen et al.'s [8] review of AR in education underscores persistent technical difficulties and elevated costs associated with deploying AR.

Consequently, educators typically need to embed AR within a broader program of learning activities to ensure its use is both contextualized and pedagogically meaningful [25]. There is a need for research into the integration of AR and pedagogy, with attention to diverse learner characteristics and impacts on both academic achievement and twenty-first-century skills [19,41]. Although research on AR in educational contexts has historically focused on adult learners, recent years have seen a marked increase in studies involving K-12 settings, coupled with predictions of expanded adoption across all educational levels [48]. Wen et al. [52] emphasize that while AR technologies offer utility, their effectiveness hinges upon strategic pedagogical application—particularly regarding higher-order thinking and the cultivation of 21st-century skills. There are many possible methods for integrating technology and pedagogy depending on desired learning outcomes. For instance, active learning approaches can encourage engagement with content through activities structured at various cognitive levels.

The current rate of technological change is extremely rapid, and teachers need to become expert at integrating transformative technologies such as AI, AR, and VR into classrooms. Ongoing professional development is recognized as crucial to help teachers integrate technology effectively [50]. Previous researchers such as Salehi [39] highlight the importance of professional development to support teachers in effectively implementing AR and call for applied research across contexts to document it. Küng & Brovelli [25] explore the impact of AR teacher training and advocate for facilitators to act as role models, to provide hands-on experience with the technology, and to give practical use examples.

Piedade and Batista [32] also discuss the need to provide teachers with opportunities to receive professional training for incoming technologies such as AR and note that many teachers appreciate the pedagogical possibilities of the technology but feel unsure how to incorporate it. Furthermore, they support the role of combining model lessons with peer mentoring and hands on learning so as to provide an opportunity to “combine technical skill-building with pedagogical design” (p. 12). The current research, teachers learned through practicing hands on in the role of students and then reflecting on the experience in relation to theory to better assist them in developing transferable TPACK for continuing changes to technology and content. Adapting to new instructional technologies requires time, patience, and structured support. Without targeted training, educators may feel overwhelmed, especially in already demanding K-12 environments, reducing the likelihood of successful adoption [4].

To guide the research, the central research question: “What understandings can be uncovered regarding teacher professional development for technological integration by demonstrating how TPACK functions using a differentiated station-based learning design that includes augmented reality?” was utilized.

3. METHOD

3.1. Context

The research took place in a bilingual high school in Beijing, China, in which all teachers have access to a shared AR laboratory. Software offerings encompass subjects including biology, chemistry, physics, multidisciplinary STEM fields, social sciences, sustainable development, literature, and

introductory 3D design. These resources support both standalone lessons and integration into extended instructional workflows.

3.2. Theoretical Framework

The theoretical framework for this research was the Technological Pedagogical Content Knowledge (TPACK) framework, developed by Koehler and Mishra [24]. This framework conceptualizes the multifaceted knowledge required for effective teaching with technology. TPACK posits that meaningful educational technology use arises from the intersection of three primary knowledge domains: content knowledge (CK), pedagogical knowledge (PK), and technological knowledge (TK). These three primary domains interact to create a total of seven domains. The framework emphasizes that successful teaching with technology necessitates not only an understanding of subject matter and pedagogical strategies but also an awareness of how technology can transform and enhance the representation, delivery, and accessibility of content. Within TPACK, the synergy among these domains enables educators to design and implement learning experiences that are contextually relevant, pedagogically sound, and technologically appropriate, thereby supporting diverse learners and promoting deeper engagement with curricular objectives.

Shulman's Pedagogical Content Knowledge (PCK) framework (1986), provides the foundation for TPACK and posits that effective teaching requires not only mastery of subject matter but also a nuanced understanding of how to represent and communicate that content (CK) to diverse learners using appropriate pedagogy (PK). The PCK framework highlights interaction with subject knowledge that is pedagogically powerful and adaptive to students' prior knowledge, interests, and learning context. As a foundational concept in teacher education, PCK underscores the complex, integrative knowledge base necessary for high-quality instruction across disciplines.

3.3. Participants

Ten teachers from a bilingual high school, teaching Years 10–12 were included in the research. Participants were recruited using an open call for faculty interested in learning about integration of AR and participating in the research. Participation was voluntary and not dependent on contributing data to the research. Informed consent was obtained. All data was anonymized.

3.4. Procedure

For this research, as the participants who requested participation were primarily English teachers, a module relevant to their discipline was chosen for target knowledge. In this case a "Hero's Journey" module based on Joseph Campbell's [7] work *The Hero with a Thousand Faces*, was selected as a potential literature lesson for high school English classes. The AR module allowed participants to view a virtual representation of the Hero's Journey conceptual framework in 3 dimensions, break it down into component parts, and physically manipulate or reorder the components while simultaneously examining complimentary text and answering questions on the computers. The participating teachers used the AR computers in the role of students while the PD instructor demonstrated utilizing the AR as a teaching assistant to free up the teacher for coaching as well as supporting the visualization of the core learning goal concept (the phases of the Hero's Journey) through the technology.

However, the AR module was incorporated into a larger station-based workflow. Learning activities were organized into six stations, each representing a different level of Bloom's Taxonomy (1956). The first station was a vocabulary primer to help participants remember the components of the framework, and the stations progressed up to a final step in which the task the production of a short story of any genre demonstrating the features of the Hero's Journey model was required. As participants progressed through the stations at their own pace, they received individual formative feedback and coaching using a combination of traffic lights and facilitator direction.

Teachers enrolled in the professional development participated as students without a primer, providing them a student perspective on the combination of technology, pedagogy, and content. After completing the workflow, they were invited to reflect on their learning, connect it to the TPACK framework, and connect the experience with the how they might use technology in their own classrooms, for their own content.

3.5. Data Collection

Collecting data from multiple sources is essential to obtaining a comprehensive understanding of participant experiences. Interpretivist paradigms acknowledge that external reality is filtered through individuals' perceptions, necessitating the inclusion of diverse perspectives to enhance validity and reliability [12]. Triangulation involves leveraging multiple types and sources of data to broaden and deepen understanding [11]. This study integrated survey responses, semi-structured interviews, observational data, and researcher notes to provide multi-faceted insights.

As the focus was to develop comprehensive understanding in context, a predominantly qualitative methodology was adopted. Throughout the research project, qualitative research notes were recorded into a digital reflective document. During the professional development, two observers collected qualitative notes. The first observer was focused on moment-by-moment data collection using a prepared data collection form with sections separating comments on what the facilitator did and what the participants were doing including a focus on active learning; formative assessment, technology use; any problems that were detected in the pedagogy, technological use, or understanding of what was being asked; and areas of strength where the participants might have benefitted in unexpected ways. The second observer did not record notes during the session, instead focusing on watching the activity without a break in attention. The observers and facilitator met immediately after the professional development workshop to discuss what was observed and compile into a reflective digital document. Collectively, these different vantage points supported a holistic examination of the central research questions and helped uncover potential blind spots.

After the professional development, semi-structured qualitative interviews captured participants' perceptions and motivations relating to their experience and learning. Interviews enriched the dataset with personal reflection, albeit with some risk of social pressure. The semi-structured interviews used a protocol that reviewed informed consent and the right to withdraw data at any time. The interview protocol contained nine questions in total. The duration of the interviews varied depending on the length of participant responses with the shortest interview duration being 15 minutes and 43 seconds and the longest being 31 minutes and 11 seconds. Finally, the anonymous quantitative survey was provided as an additional data type to check for any social desirability bias participants might have felt during interviews. Surveys were accessed voluntarily using a QR code. Anonymous Likert-scale questions offered confirmatory quantitative data free from potential interview biases.

Sample interview questions included:

1. Compared to more traditional teaching methods, how do you perceive the effectiveness and engagement of this lesson? Please explain.
2. Do you feel more confident in designing self-paced learning activities for your subject using Augmented Reality after this professional development? Please explain.
3. Would you consider incorporating AR or other technologies into your lessons to facilitate more time for mentoring and coaching students? Why or why not?

3.6. Analysis

Qualitative data were coded thematically to create an organized narrative of findings, while survey data were analyzed descriptively [12]. As Creswell & Guetterman [11] state, "Coding is the process of segmenting and labeling text to form descriptions and broad themes in the data" (p. 243). Similarly, Saldaña [38] notes "coding is to detect patterns in the data" (p. 77). In the initial stage, interview recordings were transcribed and responses were initially categorized according to interview prompts. During the next stage, key quotes from each participant were categorized again and labelled with codes. In the third stage, several major themes were drafted based on the collected codes which were then refined through discussion with colleagues, resulting in five primary themes: Pedagogical knowledge, content knowledge, technological knowledge, training in the role of students, and future of education. Originally, other TPACK subdomains were noted as themes. However, these were eventually collapsed into the primary domains to enhance clarity. In the fourth stage, corresponding key quotes from participants were extracted and placed under each theme-code combination. A final review included identifying key quotes from the database to strengthen exemplify the evidence for claims.

4. FINDINGS

4.1. Qualitative Data

4.1.1. Theme 1: Pedagogical Knowledge

Development of pedagogical *knowledge* was the theme most commented on. This is likely because only some elements of the lesson were technologically mediated and also because the technology was purposefully used as a tool for advanced pedagogy, which was one of the learning goals of the professional development. It was noted by all the participants that training in using an extended Assessment as Learning workflow with pace-differentiated stations that progressively moved through learning activities rooted in a range of thinking moves was beneficial pedagogical learning and there was self-assessed insight into transferring the learning to their own classrooms where appropriate.

As part of this learning, the participants came to a better understanding of how individualized coaching and self-pacing work practically. The individual coaching supported effective formative assessment and feedback and the participants all felt that the pedagogy had value in their own classrooms. For example, participant 2 stated:

I think it's [learning stations with coaching] an effective way because it improves student engagement and allows the teacher to give individualized coaching for every student. Also for the learning outcomes because the teacher is right there helping their students with their assessment. So, learning outcomes will be definitely better than in a regular class.

Another key facet of the experience was that the participants felt the pedagogy gave them more time for thinking. For example, participant 5 stated:

"I realized that I really need a lot of learning... You know, it provided me an opportunity to reflect on myself, and it gave me a lot of time to think... you're providing the opportunity to think by myself. You provide time and you don't push us. You very patiently to leave us to do it. But if we have any questions, you will also come to us, so I think that's very good."

The gradual increase in complexity as the students moved through the stations was noted as both engaging and useful pedagogically. Participant 7 described this as:

I think the most important insight would be how to gradually work up to completing the objectives through multiple stations. The first part was mainly just vocabulary... and I liked how the next part was getting the visual aspects on the AR... And then after that, putting it together with the animation and creating your own story. So, I like how it gradually builds up and it wasn't too much at once.

Some participants thought it might be difficult to translate the pedagogy into larger class sizes. Participant 3 noted:

I thought it worked pretty well for the smaller number of students that we had in that class. It was very easy to go from station to station and you're really attentively making sure everybody knew what they needed to do at each station. If you had a larger class, it'd be difficult to make sure every student was doing what they needed to do... to make sure that you could answer all the questions in, like, a timely manner.

4.1.2. Theme 2: Content Knowledge

The analysis found that all participants successfully learned the content knowledge in utilizing the Hero's Journey for comparative mythology and literary analysis. This was identified as useful by participants both from the perspective of professional development for themselves and also useful for future students. This learning was identified through a combination of participant self-assessment, researcher formative assessment, observer formative assessment, and completion of the training workflow.

4.1.3. Theme 3: Technological Knowledge

All participants noted that the use of AR positively impacted their learning by engaging them and providing a structure for individualized, self-directed learning. The combination of pedagogy and

technology was universally found to be appealing. Participant 3 noted: *“It was really fun, to be honest. Like, if I was a student, I would want to be in that class. It was just really interesting”*.

The participants also noted that the AR system acted effectively as a teaching assistant, with the technology facilitating the pace differentiation that supported pedagogy such as planned thinking move stations [37] and dialogic coaching [13]. Participant 1 explained:

I think this [AR] is a really, you know, a creative and genius process to draw out attention from your students for their engagement... most students in China, including students in our school, have never experienced a system in which they learn something by themselves, especially self-paced learning, which I think it is really impressive.

Another finding was that technological tools, particularly those with pedagogical affordances like AR, require practice to use for teaching and learning effectively, which was noted by all the participants. Some participants felt that they learned that students using AR technology for the first time also required explicit instruction in how to use it. Participant 5 noted: *“I didn’t know that I had to wear the glasses or that I had to use the pen to select things right. So, I think as a very first experience, maybe that could have explained before I got to the station”*.

While participants supported incorporating innovative teaching methods and that felt that integrating self-paced learning with AR has the potential for beneficial impact, most agreed that more professional training in these technologies was needed to help them feel more confident in matching their teaching and learning approach to both technological affordances and content.

4.1.4. Theme 4: Training in the Role of Students

Many of the teachers noted how training in the role of students gave them insight they did not usually get in professional development programming. For example, participant 5 stated:

Had it [AR] just been explained to me... I may not have looked into it or tried to use it. But actually being in the students’ shoes and going through it, because of that, I think I can see how it would definitely be useful, especially for my lower-level students.

Participant 8 described the experience of being in the role of the student as useful both for the pedagogical and technological knowledge:

Demonstrating it from the point of view of being a student rather than like, you know, learning about a new concept and then maybe going directly to try to design something. Maybe that’s not going to be as effective. And so, taking the role of the student to understand the student habits. And the AR stuff is very... I’m very much curious about that. Because I haven’t really done too much with that technology. So definitely curiosity how some of these tools work and what exactly is available.

4.1.5. Theme 5: Future of Learning

Several of the participants drew conclusions that the combined model of individualized, technologically mediated, self-paced learning with human teachers for coaching, formative assessment and feedback, and collaborative real world integrative activities were likely to be, as participant 1 put it: *“the future of teaching and learning for our globe”*.

When considering the future, particularly with individualized success metrics and artificial intelligence, it is important that some participants noted that the gamification of the learning progression pushed them to focus deeply on the learning whether due to a sense of competition with classmates or an internal drive to complete the stations. This drive to engage with content due to pedagogy and technology ended up drawing the participants into the learning even if they were not innately interested in it. For example, participant 5 described the experience as:

I think it’s definitely a lot more engaging. I think traditionally, it’s easy to sort of fall back. So, for example, in my personal experience, the content of this is of no interest to me, right? It’s not something that I am at all interested in. So traditionally, I would have just sat back and probably played on my phone, to be honest. So now, in this style of class, it sort of forced me to read. Because I think there is an underlying thing of like, oh, I have to get, I want to get to the end. Like I want to make it to the last station. So, if I’m just going to not do it, well, I just

sit here at the first station. So, in a good way, but you know, I feel like... people are moving, so let me do it. And then I start reading, and actually it is kind of interesting. Actually, I do kind of know an answer to this. Where traditionally I would have failed out instantly because this is something I'm not interested in.

However, this sense of pressure was not universally experienced as pleasant. Several participants noted it was stressful to them so see how others were progressing faster than them and they extrapolated their own students might feel stress as well. For example, participant 2 suggested:

I feel if someone is really competitive and sitting beside you, that may cause some students high pressure and fear of asking for help because someone is doing too good. So... I think maybe in the future could give more instructions or help to get rid of that competitive atmosphere.

This type of issue may become increasingly important in the age of big data, artificial intelligence, and individualized learning.

4.2. Quantitative Data

The quantitative data was predominantly gathered to check the results of qualitative data. Therefore, the most important finding from the anonymous questionnaire was that the data supported the qualitative responses. Likert scales were standardized with a 1 indicating strongly disagree, 2 indicating disagree, 3 indicating neutral, 4 indicating agree, and 5 indicating strongly agree. Some key responses include the following:

I learned about self-paced learning using augmented reality ($M = 4.8$, $SD = 0.4$).

Learning the content knowledge of the Hero's Journey framework supported by 3 dimensional models in augmented reality enhanced my learning ($M = 4.7$, $SD = 0.64$).

I believe I could use elements of this lesson in my own classroom to improve learning ($M = 4.9$, $SD = 0.3$).

I would like to design some self-paced learning activities ($M = 4.9$, $SD = 0.3$).

5. DISCUSSION

In this case, augmented reality (AR) enabled self-paced learning, allowing teachers to offer more individualized support to students and allowing students to move through a progressive workflow of thinking moves in a way that suited their learning preferences. The findings generally support the literature [49]. Like, Zhang et al. [55], the participants felt that AR inquiry-based activities encourage student engagement in knowledge construction compared to traditional approaches. Akçayir & Akçayir [1] noted that AR may contribute to learning motivation, comprehension, positive attitudes, and satisfaction, which could be factors promoting sustained self-directed learning with AR and the participants noted these attributes. As an emerging technology, AR has demonstrated potential effectiveness in self-guided learning contexts [51]. Nonetheless, when implementing AR with student participants, aspects such as classroom management, technology use discipline, and safety require further consideration. It is particularly important to distinguish between engagement and effective learning outcomes. In this case effective learning was uncovered using formative assessment reinforced by dialogic feedback. Regardless of technology, an awareness of formative assessment remains essential and should align with learning objectives.

The research supported previous work finding AR can effectively present abstract concepts or information suited to three-dimensional visualization. Prior research [4] supports AR's potential to facilitate understanding this kind of learning goal through interactive experiences and this was observed in the current inquiry. This observation aligns with literature suggesting that AR can aid in visualizing complex spatial relationships and enhance understanding of spatial concepts [45]. However, challenges exist, such as the risk of cognitive overload if students receive excessive information in the AR environment [14]. Santos et al. [42] indicated that by controlling the amount of information presented in AR, cognitive load can potentially be reduced. Emerging trends suggest that combining adaptive AI with AR/VR could enhance responsiveness and immersion by tailoring virtual content to user interactions [46].

Multiple recent studies have emphasized the necessity of training and professional development for teachers to integrate AR effectively into classrooms [25,32,39]. This work supports those recommendations and extends them. In this context, while AR offered pedagogical affordances, successful implementation still depended on teacher proficiency integrating the technology in a broader pedagogical strategy, highlighting the need for ongoing training and practice in combining content, pedagogy, and technology effectively. Various strategies, including self-paced and differentiated learning artifacts, were employed in the workshop design. This approach is consistent with Jesionkowska et al. [22], who recommended professional development to enhance educators' confidence and skill in using AR with active learning as the design foundation. Effective delivery of professional development is important for closing the gap between theory and practice, and modelling experiences that future students may have has been effective in previous literature for this purpose [17]. This builds on Küng and Brovelli's [25] recommendation of modelling impactful pedagogy utilizing hand-on role play as one means of effective AR professional development by clarifying an important role that teachers can take, which is that of their future students.

Modeling high impact practices was effective in supporting subject teachers in understanding new instructional strategies given the technology under study but also the concept of transfer across technologies, pedagogies, and content areas [24]. This is crucial as technologies continue to transform, merge, and combine with content that increasingly moves from disciplinary to multidisciplinary or interdisciplinary. As concern about technical elements of AR use have been noted in the literature [32], it was important that the potential for technology and pedagogy to come together as a motivating and beneficial force was noted by the participants and they were able to overcome technical challenges with support and thereby both learn the technical elements and how they might provide technical support in future. However, it should also be noted they raised concerns about some of the potential negative repercussions of competition and gamification that could emerge, especially as artificial intelligence fuses with computer assisted learning.

The research is limited in many ways. The findings presented in this paper are based on a single case study and are therefore not meant to be generalizable. Another limitation is the small participant sample, which means that the findings may not be reliable. Also, the long-term training impact was not evaluated after in the classrooms of the participating teachers but instead indirectly through self-assessment in interviews and through observations of their own performance in the role of students.

6. CONCLUSIONS

Despite limitations, the insights gained offer valuable perspectives for the integration of innovative educational technologies within similar learning contexts. The findings suggest that pedagogically focused workshops that combine hands-on roleplaying with reflection on content, technological, and pedagogical interactions can have a meaningful impact on participant engagement and attitudes toward new technological tools as well as supporting a move from theoretical understanding of TPACK toward the ability to understand it from a more practical standpoint.

The unique physical manipulation aspects of AR make it particularly important for teachers to experience so they can anticipate difficulties and support students effectively. This case study also highlights the importance of modelling pedagogy and of reflective discussion in fostering both understanding and acceptance of technological interventions among educators and students alike.

While generalizations are not possible, the positive outcomes observed underscore the potential for scalable application in diverse educational settings. As the landscape of education continues to evolve with the intersection of augmented reality, artificial intelligence, and competency-based learning with personal AI tutors, it can be expected that this type of personalized pedagogy will become more popular as computer mediated learning with intelligent agents free classroom teachers to provide more individualized support and coaching. Coaching practices take time to develop and may be supported by utilizing professional development and resources such as Dochý et al. [13]. Future research using a similar pedagogy/andragogy in a variety of other contexts would help create a more comprehensive understanding than is possible with a single case study. However, as technological progress in AI is moving quickly, it may be of higher priority to explore the use of similar pedagogy in conjunction with AI teaching systems (with-or-without AR capabilities) at this juncture. Furthermore,

it is imperative to maintain a critical lens that considers both opportunities and challenges of pedagogical moves such as technology-mediated pace differentiation with human coaching. Researchers, policymakers, and educators ideally should collaborate through ongoing applied research to ensure that technological advancements are aligned with pedagogical goals such as deep thinking, ensure equitable access, and build in ethical safeguards against harms that may emerge such as negative repercussions of hyper-competitive designs or other emerging issues such as biometric data collection and digital academic integrity.

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