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Augmented reality competencies and integration challenges among primary school teacher education students: a mixed-methods study

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ABSTRACT

Introduction. In the digital age, integrating advanced technologies like Augmented Reality (AR) into educational practices is increasingly vital. AR holds the potential to significantly enhance student engagement and understanding by providing immersive learning experiences. This study investigates the AR competencies among Primary School Teacher Education (PSTE) students and identifies the challenges they face in incorporating AR into their teaching practices.

Study participants and methods. The study involved 150 PSTE students who participated in a comprehensive mixed-methods approach comprising surveys, interviews, and classroom observations. Quantitative data were analyzed using descriptive and inferential statistics, including means, standard deviations, and ANOVA to examine competency levels and confidence differences. Qualitative data from interviews and observations were coded and analyzed thematically to uncover deeper insights into participants' experiences.

Results. The findings revealed varied levels of AR competencies among the participants: 20% demonstrated minimal competencies, 46.7% had moderate competencies, and 33.3% exhibited extensive competencies. Significant differences in confidence levels were observed across these competency groups. Participants acknowledged AR's potential to enhance student engagement and understanding; however, they faced several challenges, including insufficient training (63.3%), technical difficulties (56.7%), and limited access to AR devices (60%). Qualitative analysis underscored the need for better support and resources to effectively integrate AR into educational settings.

Conclusion. The study underscores the importance of comprehensive professional development programs that address both the technical and pedagogical aspects of AR integration. To maximize AR's educational potential, teacher education programs must prioritize robust training and resource allocation. The findings suggest actionable strategies for improving AR competency among PSTE students and highlight areas for future research, including longitudinal studies on AR's impact on teaching efficacy and student outcomes.

KEYWORDS

augmented reality, teacher education, primary education, professional development, mixed-methods research

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INTRODUCTION

The digital revolution has ushered in a new era of educational possibilities, with technology increasingly intertwining itself into the fabric of our learning environments [1; 2]. Augmented Reality (AR) stands out as a captivating and transformative force among the myriad technological marvels reshaping the educational landscape. This cutting-edge technology, which seamlessly blends digital elements with our physical surroundings, can revolutionize how we teach and learn, offering an immersive and interactive experience that transcends the limitations of traditional pedagogical approaches.

Imagine a classroom where abstract concepts materialize before students' eyes, historical events unfold in vivid detail, and complex scientific phenomena can be manipulated and explored with the touch of a finger. This is the promise of AR in education – a world where the boundaries between the tangible and the digital blur, creating a rich tapestry of learning opportunities that engage multiple senses and learning styles [3; 4].

The implications of this technological renaissance are particularly profound in teacher education [5]. As we stand on the cusp of this educational paradigm shift, it becomes increasingly crucial to equip our future educators with the tools, knowledge, and competencies necessary to harness the full potential of AR in their classrooms. After all, these aspiring teachers will be the vanguards of innovation, tasked with preparing the next generation for a world where the integration of digital and physical realities is not just commonplace but essential.

Recent scholarly endeavors have illuminated AR's transformative power in various educational contexts. For instance, the groundbreaking work of Garzón et al. [6] has shed light on AR's remarkable ability to ignite students' motivation and engagement, leading to a notable uptick in academic performance. This research paints a picture of classrooms buzzing with enthusiasm, where students are not passive recipients of knowledge but active participants in their learning journeys.

Building upon this foundation, Álvarez-Marín and Velazquez-Iturbide [7] have further expanded our understanding of AR's educational potential. Their research highlights AR's unique capacity to demystify complex concepts through vivid visualizations and interactive features. Imagine students grasping the intricacies of cellular biology by manipulating 3D models of organelles or unraveling the mysteries of quantum physics through immersive simulations. These findings underscore the urgent need to incorporate AR training into teacher education programs, ensuring our future educators can leverage this tool in their pedagogical arsenal.

The chorus of voices extolling the virtues of AR in education continues to grow. Garzón and Acevedo's [8] comprehensive meta-analysis offers a bird's-eye view of AR's impact on educational outcomes, revealing its particular efficacy in nurturing spatial abilities and fostering dynamic, interactive learning environments. This research paints a picture of classrooms transformed into vibrant laboratories of discovery, where abstract concepts take on tangible form, and students can reach out and touch their learning.

Özçelik et al. [9] have illuminated AR's potential to bridge the gap between theory and practice in science education. Their work suggests that AR applications can significantly enhance students' conceptual understanding and engagement by providing hands-on, experiential learning opportunities. Imagine students exploring the depths of the ocean floor, dissecting virtual specimens, or conducting hazardous experiments in a safe, controlled AR environment. The possibilities are as boundless as our imagination.

However, a glaring gap in our knowledge emerges amidst this growing body of evidence supporting AR's educational potential. While much attention has been paid to AR's impact on student learning, the readiness and competencies of pre-service teachers to leverage this technology remain largely unexplored territory. This oversight is brought into sharp focus by the work of Avila-Garzon et al. [10], which highlights a troubling lack of adequate training and support for teachers in integrating AR into their pedagogical practices.

This knowledge gap represents a critical challenge in teacher education, particularly in the context of Primary School Teacher Education (PSTE). As we stand on the precipice of a new educational era, we must equip our future primary school educators with the skills and confidence to harness the power of AR in their classrooms [11; 12]. Without addressing this gap, we risk creating a generation of teachers ill-prepared for the technological realities of modern education, potentially widening the digital divide and leaving countless students behind.

To navigate this uncharted territory and bridge the chasm between technological potential and pedagogical practice, we must embark on a journey of discovery. We need to delve deep into the AR competencies of pre-service teachers, exploring their readiness, attitudes, and skills in integrating this transformative technology into their future classrooms. By doing so, we can ensure that the next generation of educators is not just keeping pace with technological advancements but also revolutionizing primary education.

As we begin this research endeavor, several pivotal questions emerge, begging for exploration and illumination. These questions will serve as our compass, guiding us through the complex landscape of AR in teacher education:

1. What is the current level of AR skills among PSTE students?
2. How do PSTE students perceive the use of AR in teaching and learning?
3. What challenges do PSTE students face in integrating AR into their instructional practices?
4. What are the implications of AR competencies on the effectiveness of teaching practices among pre-service teachers?

This study holds significant importance for several reasons. First, it comprehensively evaluates AR competencies among PSTE students, offering insights into their readiness to incorporate AR technology into their teaching practices. Second, the findings will inform the development of targeted training programs and support mechanisms that can enhance pre-service teachers' skills in using AR, ultimately leading to more effective teaching strategies. Third, by addressing the identified challenges, the study will contribute to the broader discourse on integrating innovative technologies in teacher education, ensuring that future educators are well-equipped to meet the demands of modern classrooms.

LITERATURE REVIEW

1. Augmented Reality in Education

Augmented Reality (AR) is a major advancement in educational technology, offering an interactive way to improve conventional learning settings. AR enables learners to engage in a rich combination of real and virtual experiences by superimposing digital content onto the physical world. This new method can help make complex ideas easier to understand and education more engaging. For example, Garzón and Acevedo [8] have highlighted how AR improves students' comprehension and memory through engaging learning settings that promote involvement. This is especially advantageous in science and mathematics, where intricate theories and procedures can be visualized and examined in ways that conventional methods may not facilitate.

AR goes beyond just enhancing student results; it also provides beneficial chances for teacher training. Although its potential is high, incorporating AR in teacher training programs lacks in-depth investigation. Even though previous studies show the advantages of AR in student education, they also point out a crucial lack of training for future teachers to use this technology efficiently. As the industry progresses, exploring how future teachers can be prepared to use AR effectively in their upcoming classrooms is more crucial. This research aims to fill the void by investigating students' abilities in studying Primary School Teacher Education and examining their encounters with AR. The research seeks to improve the current knowledge of how AR can be incorporated into teacher training, ultimately closing the gap between technological advances and practical use in education settings.

2. AR and Student Learning Outcomes

Recent research has focused on the effect of AR on student learning results, emphasizing its capability to enhance educational experiences greatly. Research like the one conducted by Garzón et al. [6] has shown that augmented reality (AR) can result in higher levels of student motivation, participation, and academic achievement. AR applications allow students to visualize and manipulate information in ways that traditional teaching methods may not facilitate due to their interactive nature. This aligns with constructivist learning theory, which proposes that learners construct understanding better through practical, contextualized experiences. Özçelik et al. [9] provide additional evidence by demonstrating that AR in science education boosts students' comprehension and curiosity in intricate scientific ideas, supporting the notion that interactive, immersive learning encounters can result in greater understanding.

This study on student results lays a solid groundwork for grasping the possible advantages of AR while also pointing out the necessity for similar progress in teacher training. Although the benefits of AR in enhancing student learning are well-established, there is limited understanding of how to train teachers to utilize this technology effectively. The study aims to enhance knowledge by examining how pre-service teachers can incorporate AR into their teaching methods. The research will provide valuable insights into the effective use of AR in enhancing student learning and supporting teacher preparation programs by examining the competencies and experiences of PSTE students. This method will make sure that the advantages of AR are completely experienced in teaching and learning settings.

3. AR in Teacher Education

The incorporation of AR into programs for training teachers is an area that has not been thoroughly examined, even though it has the potential to change how teachers teach completely. Recent research highlights a noticeable deficiency in training pre-service educators in utilizing AR technology effectively. Avila-Garzon et al. [10] point out that numerous teacher education programs do not provide thorough training on AR, causing a gap between the presence of technological tools and their effective use in school settings. This gap shows the need for specific professional training and curriculum planning to effectively prepare upcoming teachers with the skills to incorporate AR into their teaching methods.

It is crucial to address this gap so that pre-service teachers are ready to use AR in their upcoming classrooms. The current research seeks to address this gap by evaluating the AR skills of pre-service teacher education students and investigating their views on incorporating AR into instruction. Using a combination of research methods, this study will offer a detailed insight into how pre-service teachers engage with AR and pinpoint areas that may require extra training or resources. This contribution is essential for creating teacher education programs that integrate new technologies and help educators utilize these tools to enhance teaching practices and boost student learning outcomes.

4. Theoretical Frameworks

The theoretical foundations supporting the adoption of AR in education provide an important understanding of how this technology can be successfully incorporated into educational practices. Constructivism, advocated by Piaget [13], highlights that students build their knowledge by engaging in experiences and reflecting on them. AR supports this idea by allowing future teachers to interact with digital materials in practical situations, leading to a better understanding of teaching concepts. This method enables upcoming teachers to test and contemplate the effects of AR in a real-world environment, improving their teaching methods with engaging and immersive encounters.

Active learning is a theory that suggests students learn better when they actively participate in their educational tasks, as stated by Bonwell & Eison [14]. Augmented reality supports active learning by allowing future teachers to create and execute engaging lessons that involve students meaningfully. Likewise, Suadiyatno et al. [15] suggest in their contextual learning theory that students achieve optimal learning when new information is introduced in a meaningful and understandable context. AR's ability to superimpose digital content onto physical surroundings makes it a perfect tool for developing contextualized educational experiences. The study aims to investigate how AR can improve teaching methods and impact teacher education programs by using these theoretical frameworks.

The literature review highlights the big potential of AR to improve educational results and the urgent requirement for its inclusion in teacher training programs. Although AR has proven to enhance student participation and educational outcomes, its utilization in teacher training has not been thoroughly investigated. This research aims to fill this void by examining the AR skills of pre-service teachers and their interactions with AR in the classroom. The research aims to improve future educators' training and support by assessing these factors and incorporating theoretical frameworks like constructivism, active learning, and contextual learning. This article is crucial for promoting adopting new technologies in education and ensuring that teacher training programs match current educational methods.

METHODOLOGY

1. Research Design

This research employed quantitative and qualitative methods to thoroughly explore Augmented Reality (AR) competencies among students studying Primary School Teacher Education. The structured surveys were used for the quantitative aspect to evaluate the current AR skills. At the same time, in-depth interviews and observations were employed for the qualitative aspect to investigate students' views, difficulties, and practical use of AR in teaching. This integrated method permitted a thorough examination, utilizing the advantages of each approach. Quantitative data gave broad statistical insights into AR competencies, while qualitative data provided a more in-depth, contextual understanding of participants' experiences and challenges [16].

2. Participants

The research included 150 students in a university teacher education program, chosen using stratified random sampling to represent different years of study and specializations. This sampling approach was designed to encompass a variety of experiences with AR technology. Participants were selected from students in their first to final year of studies, aiming for a diverse representation of male and female students and students of various ages and technology backgrounds. The participants' demographic characteristics were the following:

Table 1

Demographic characteristics of PSTE students

Demographic Variable	Category	Number of Participants	Percentage (%)
Year of Study	First Year	40	26.7
	Second Year	35	23.3
	Third Year	30	20.0
	Final Year	45	30.0
Gender	Male	60	40.0
	Female	90	60.0
Age	18-22	80	53.3
	23-30	50	33.3
	31+	20	13.3
Prior Technology Experience	Minimal	30	20.0
	Moderate	70	46.7
	Extensive	50	33.3

Participants varied in their prior experience with technology, ranging from minimal exposure to extensive use, which provided a broad perspective on AR competencies and integration. This diversity in background and experience helped ensure a comprehensive analysis of AR's impact on teacher education.

3. Instruments

The study utilized a combination of surveys, interviews, and observation checklists to address the research questions. A structured questionnaire was developed to assess various dimensions of AR skills among PSTE students, including technical abilities, pedagogical knowledge, and application skills. The validity of the survey was established through expert review and pilot testing with a small group of PSTE students, which ensured that the questions were relevant and comprehensively covered the intended constructs [17]. Reliability was assessed using Cronbach's alpha, with a target value of 0.70 or higher, to ensure internal consistency [18].

Semi-structured interviews explored PSTE students' perceptions of AR in teaching and learning. The interview guide included open-ended questions to facilitate detailed discussions about participants' experiences and attitudes. The interview protocol was validated through a review by experts in educational technology, and reliability was maintained through consistent interviewer training and a rigorous coding scheme. Additionally, observation checklists document how PSTE students integrated AR into their teaching practices. These checklists were developed and validated through pilot observations and feedback from specialists, ensuring they accurately captured relevant aspects of AR use in instructional settings.

4. Data Collection

Data collection occurred in several phases. Surveys were distributed electronically to all participating PSTE students, who had two weeks to complete them. Reminders were sent at one-week intervals to enhance response rates. The survey data were analyzed quantitatively to assess the overall AR skill levels among the students. Following the survey, a subset of participants was selected for interviews based on their survey responses and willingness to participate. Depending on participants ' preferences, interviews were conducted in person or via video conferencing. These interviews were recorded and transcribed for detailed analysis.

Classroom observations were scheduled with participants actively using AR in their teaching practices. Observers used a structured checklist to record data on engagement levels, instructional strategies, and student interactions. This observational data was compiled and analyzed to identify common patterns and challenges related to AR integration.

5. Data Analysis

Quantitative data from the surveys were analyzed using descriptive statistics to summarize AR competencies and inferential statistics, such as t-tests or ANOVA, to explore differences based on demographic and educational variables. Statistical analysis was conducted using software such as SPSS or R [19]. For qualitative data, thematic analysis was employed to identify and analyze recurring themes and patterns in the interview and observation data. This analysis followed Braun and Clarke's [20] guidelines, including familiarizing the data, generating initial codes, searching for themes, reviewing themes, and writing the report. The iterative process of thematic analysis and peer debriefing enhanced the credibility and reliability of the qualitative findings.

6. Ethical Guidance

Ethical considerations were paramount throughout the study. Informed consent was obtained from all participants, clearly outlining the study's purpose, procedures, and potential risks. Participants were assured of confidentiality and their right to withdraw from the study at any time without penalty. Data were anonymized and securely stored by institutional ethical guidelines and data protection regulations [21]. The study also received approval from the university's institutional review board (IRB) to ensure adherence to ethical research practices. These measures ensured that the research was conducted with respect for participants and rigor in its approach. Overall, the methodology provided a comprehensive and nuanced understanding of AR competencies among PSTE students and their implications for teaching practices. Through the combined use of quantitative and qualitative methods, the study effectively addressed the research questions and contributed valuable insights to the field of teacher education.

RESULTS

1. Overview of AR Competencies Among PSTE Students

The quantitative survey data revealed a spectrum of AR competencies among Primary School Teacher Education (PSTE) students. The competencies were categorized into minimal, moderate, and extensive. The distribution of these competencies is summarized in Table 2.

Table 2

AR competencies among PSTE students

Competency Level	Number of Participants	Percentage (%)
Minimal	30	20.0
Moderate	70	46.7
Extensive	50	33.3

The data shows that while some PSTE students demonstrated moderate to high technical abilities in AR, there were notable gaps in their pedagogical knowledge and application skills. A one-way ANOVA was conducted to compare the confidence levels across the different competency groups and further understand the differences in AR competencies.

(H0): There is no significant difference in confidence levels across the AR competency groups.

(H1): There is a significant difference in confidence levels across the different AR competency groups.

The one-way ANOVA test results are summarized in Table 3.

Table 3

ANOVA test results for confidence levels across AR competency groups

Source of Variation	The sum of Squares (SS)	Degrees of Freedom (df)	Mean Square (MS)	F-Value	p-Value
Between Groups	34.72	2	17.36	8.35	< .001
Within Groups	305.88	147	2.08		
Total	340.60	149			

A one-way ANOVA revealed significant differences in confidence levels across different competency groups ($F(2, 147) = 8.35$, $p < .001$). Since the p-value is less than .001, we reject the null hypothesis. This indicates significant differences in confidence levels across the different competency groups. A post hoc comparison using the Tukey HSD test was performed to identify where these differences lie. The post hoc Tukey HSD test results are summarized in Table 4.

Table 4

Post hoc Tukey HSD test results

Comparison Groups	Mean Difference (M1 - M2)	Standard Error (SE)	p-Value	Confidence Interval (95%)
Extensive vs. Minimal	1.8	0.26	< .001	1.14 to 2.46
Extensive vs. Moderate	0.8	0.21	< .01	0.38 to 1.22
Moderate vs. Minimal	1.0	0.25	< .01	0.46 to 1.54

Students with extensive AR experience had significantly higher confidence levels (M = 4.1, SD = 0.8) than those with minimal experience (M = 2.3, SD = 1.0). Based on the data and the statistical analysis, the study concludes significant differences in confidence levels among PSTE students with different AR competencies. Specifically, students with extensive AR experience exhibit significantly higher confidence levels than those with minimal experience. Consequently, the null hypothesis is rejected, affirming the presence of significant differences in confidence levels across the competency groups.

This finding underscores the need for targeted training programs to enhance AR competencies, particularly focusing on bridging pedagogical knowledge and application skills gaps among PSTE students. Such initiatives will better prepare future educators to integrate AR into their teaching practices effectively, ultimately leading to improved educational outcomes.

2. Perceptions of AR in Teaching and Learning

Interviews provided deeper insights into PSTE students' perceptions of AR, revealing its potential and the challenges associated with its integration into educational practices. Most participants viewed AR as a valuable tool for enhancing student engagement and understanding complex concepts. Participant 12 remarked, "*AR makes learning much more interactive and engaging. My students can visualize concepts that are hard to grasp through traditional methods.*" This sentiment aligns with broader research indicating that AR can significantly boost student motivation and engagement, enabling a hands-on, immersive learning experience that traditional methods often lack.

However, several concerns were raised about the accessibility and ease of use of AR technology. For instance, Participant 27 expressed, "*Without proper training and resources, it's challenging to integrate AR effectively. It can be time-consuming to set up and manage during lessons.*" This reflects a common issue highlighted in the literature, where insufficient training and technical difficulties are major barriers to the effective integration of AR in classrooms. The study identified several specific challenges PSTE students face when integrating AR: insufficient training, technical difficulties, and limited access to AR devices. A significant number of participants (63.3%) reported lacking adequate training in AR technology, making it difficult to implement effectively in their teaching practices. One participant noted, "*The training we received was quite basic. We need more comprehensive workshops that cover how to use AR tools and integrate them into our lesson plans.*"

Over half of the participants (56.7%) encountered technical issues, such as problems with calibrating devices and troubleshooting software. Observational data corroborated this: "*Students often struggled with the technical aspects of AR, such as calibrating devices and troubleshooting software issues.*" Another significant barrier was the limited access to AR devices, reported by 60% of the participants. This lack of resources hinders the consistent use of AR in educational settings. One participant mentioned, "*We only have a few AR devices available, so it's not feasible to plan regular AR-based activities.*"

The findings underscore the need for targeted professional development to address these challenges. Observations indicated that students who received hands-on training were more likely to integrate AR successfully. For example, "*During a science lesson, students using AR showed higher levels of engagement and understanding of complex concepts like cellular structures compared to traditional methods.*" Additionally, the study's quantitative data revealed that while many PSTE students have moderate to high technical abilities in AR, there are notable gaps in their pedagogical knowledge and application skills. This gap was evident in the distribution of AR competencies among the students: 20% had minimal, 46.7% had moderate, and 33.3% had extensive competencies.

To effectively harness the benefits of AR in teaching, it is crucial to develop comprehensive training programs that address both the technical and pedagogical aspects of AR integration. These programs should include in-depth workshops covering the technical setup and the pedagogical integration of AR tools, ongoing support providing continuous technical support and resources to manage and troubleshoot AR devices, and ensuring adequate access to AR devices for all students to facilitate regular classroom use. By addressing these areas, teacher education programs can better prepare future educators to leverage AR technology, ultimately enhancing student learning outcomes and engagement.

Integrating AR in teaching and learning presents a promising avenue for enhancing educational experiences. However, the effective implementation of AR requires addressing significant challenges related to training, technical support, and resource availability. By focusing on these areas, educational institutions can ensure that PSTE students are well-equipped to utilize AR technology, thereby transforming their teaching practices and improving student engagement and understanding.

3. Challenges in Integrating AR

Several challenges emerged in integrating AR into teaching practices, notably insufficient training, technical difficulties, and limited access to AR devices. The feedback from PSTE students vividly illustrated these challenges, which were further corroborated by observational data.

Table 5

Challenges in integrating AR

Challenge	Number of Participants	Percentage (%)
Insufficient Training	95	63.3
Technical Difficulties	85	56.7
Limited Access	90	60.0

Insufficient training was the most frequently cited challenge, with 63.3% of participants indicating they had not received adequate preparation to use AR in their classrooms effectively. This lack of training left many students ill-equipped to integrate AR into their teaching practices. One participant articulated this issue: "*The training we received was quite basic. We need more comprehensive workshops that cover not just how to use AR tools, but also how to integrate them into our lesson plans*" (Participant 34). This sentiment highlights a significant gap in the current educational training programs, suggesting a need for more in-depth, hands-on training sessions beyond introductory overviews and practical application strategies.

Technical difficulties were another major hurdle, affecting 56.7% of the participants. These difficulties ranged from issues with device calibration to software glitches that disrupted the learning process. One observational note captured the essence of these challenges: "*Students often struggled with the technical aspects of AR, such as calibrating devices and troubleshooting software issues*" (Observation 5). These technical barriers not only impede the smooth integration of AR but also contribute to frustration and disengagement among both teachers and students. The technical complexities associated with AR require robust support systems and troubleshooting resources to ensure educators can confidently and effectively use this technology in their teaching.

Limited access to AR devices was reported by 60% of the participants, indicating a significant resource constraint. The lack of sufficient AR devices means that many educators cannot implement AR activities regularly, limiting their ability to explore this technology's potential benefits fully. One participant expressed this concern: "*We only have a few AR devices available, so it's not feasible to plan regular AR-based activities*" (Participant 45). This resource shortage hampers AR integration's consistency and reliability, making it challenging for educators to design and execute comprehensive AR-based lessons.

The observational data further reinforced these findings, highlighting specific instances where these challenges manifested in the classroom. For example, AR students experienced higher engagement and a better understanding of complex concepts like cellular structures during a science lesson than traditional methods. However, the technical and logistical difficulties often overshadowed these benefits. The observations noted that while students were generally excited about using AR, the frequent interruptions caused by technical issues and the limited availability of devices diminished the overall effectiveness of the learning experience.

The combination of insufficient training, technical difficulties, and limited access creates a substantial barrier to the successful integration of AR in educational settings. Addressing these challenges requires a multifaceted approach. Training programs need to be more comprehensive, covering both the technical and pedagogical aspects of AR. Ongoing technical support should be provided to help educators manage and troubleshoot AR devices. Furthermore, educational institutions must ensure that enough AR devices are available to facilitate regular and consistent classroom use. By addressing these challenges, teacher education programs can better prepare future educators to leverage AR technology, ultimately enhancing student learning outcomes and engagement.

4. Implications for Teaching Practices

The findings from the study underscored the critical need for targeted professional development in the use of AR technology. Students who received hands-on training successfully integrated AR into their teaching practices. This hands-on experience proved crucial in building confidence and competence among PSTE students, enabling them to utilize AR tools more effectively in their classrooms. One participant highlighted the importance of this practical training by stating, "*The workshops where we got to use the AR devices and create lesson plans were the most helpful. It gave me a clear idea of how to incorporate AR into my teaching*" (Participant 38). This direct experience with the technology helped bridge the gap between theoretical knowledge and practical application, which is essential for the effective use of AR.

Observational data provided further evidence of the benefits of AR, particularly in enhancing student engagement and understanding, especially in subjects that require visualization of abstract concepts. For instance, AR significantly boosted student engagement and comprehension during a science lesson. An observer noted, "*During a science lesson, students using AR showed higher levels of engagement and understanding of complex concepts like cellular structures compared to traditional methods*" (Observation 3). This observation highlights how AR can transform the learning experience by making abstract and complex concepts more tangible and accessible.

Additionally, students were observed to be more actively involved in their learning process when AR was integrated into lessons. Another observation noted, "*Students were more curious and asked more questions when they could see and manipulate 3D models of historical artifacts during history lessons*" (Observation 7). This increased interaction and curiosity are crucial indicators of deeper learning and engagement, suggesting that AR can significantly foster a more interactive and dynamic learning environment.

The qualitative data from interviews also reflected this positive impact. For example, a participant explained, "*When I used AR to teach geometry, my students could understand the shapes and their properties much better than when we used just textbooks and drawings*" (Participant 19). This comment underscores the potential of AR to enhance comprehension by providing visual and interactive representations of mathematical concepts, which can be particularly challenging to convey through traditional teaching methods.

However, the successful integration of AR is contingent on overcoming several barriers, primarily through targeted professional development. Effective training programs must address the technical aspects of AR tools and the pedagogical strategies for integrating these tools into the curriculum. One participant emphasized this need, stating, "*It's not enough to know how to operate the AR device; we need to learn how to use it effectively within our teaching frameworks*" (Participant 22). This highlights the dual focus that professional development programs must adopt to ensure that teachers are technically proficient and pedagogically adept in using AR technology.

Furthermore, ongoing support and resources are critical for sustaining the effective use of AR in classrooms. Observations indicated that teachers with access to continuous technical support were more confident and proficient in AR. For instance, one observer noted, "*Teachers who could rely on technical support when issues arose were more likely to use AR regularly and effectively in their lessons*" (Observation 10). This suggests that providing a robust support system can alleviate some technical challenges and encourage more consistent use of AR.

In conclusion, the study highlights the significant benefits of AR in enhancing student engagement and understanding, particularly for abstract and complex concepts. However, realizing these benefits requires targeted professional development, combining technical training and pedagogical guidance. By addressing these needs, educational institutions can better equip PSTE students to integrate AR into their teaching practices effectively, thereby transforming the educational experience and improving learning outcomes. The combination of hands-on training, continuous support, and adequate resources will be key to overcoming the challenges and fully leveraging the potential of AR in education.

DISCUSSION

The findings of this study underscore both the potential and the challenges of integrating Augmented Reality (AR) into Primary School Teacher Education (PSTE). Synthesizing the study's results with recent literature (2020-2024) provides a comprehensive view of AR's impact on educational practices.

The study's findings align with recent research highlighting AR's capability to enhance student engagement and understanding, particularly for complex and abstract concepts. For example, Garzón et al. [6] demonstrated that AR significantly boosts student motivation and engagement, improving academic performance. Álvarez-Marín and Velazquez-Iturbide [7] similarly noted that AR facilitates understanding complex concepts through interactive visualization. This study supports these findings, with participants reporting that AR made learning more interactive and engaging. Participant 12's remark, "*AR makes learning so much more interactive and engaging. My students can visualize concepts that are hard to grasp through traditional methods,*" echoes these broader research conclusions, illustrating AR's transformative potential in making abstract ideas more tangible and understandable.

However, the study also reveals significant barriers to AR integration, which are critical for a nuanced understanding of its application in educational settings. Insufficient training, technical difficulties, and limited AR device access were prominent challenges PSTE students faced [22; 23]. These findings resonate with the issues highlighted by Avila-Garzon et al. [10], who identified inadequate training and support as a major hurdle for teachers attempting to incorporate AR into their pedagogical practices. The study's observational data reinforce this, noting struggles with technical aspects such as calibrating devices and troubleshooting software issues. This indicates a pressing need for comprehensive professional development programs that equip educators with the technical skills and pedagogical strategies necessary for effective AR integration [24; 25].

Moreover, the study found that students who received hands-on training were more likely to integrate AR successfully, enhancing student engagement and understanding. This aligns with Özçelik et al. [9], who emphasized that hands-on, experiential learning opportunities provided by AR can significantly improve students' conceptual understanding and engagement, particularly in science education. The observation that "*students using AR showed higher levels of engagement and understanding of complex concepts like cellular structures compared to traditional methods*" further supports the efficacy of AR in fostering deeper comprehension through interactive, immersive experiences.

Despite these benefits, AR accessibility remains a critical issue. Limited access to AR devices, reported by 60% of participants, underscores the digital divide that can impede the equitable implementation of innovative technologies in education. This challenge aligns with broader concerns in the literature about resource availability and equity in educational technology deployment [26; 27].

Additionally, recent studies by Sırakaya and Alsancak-Sırakaya [28] highlight the necessity of institutional support and infrastructure to facilitate AR integration. They argue that even well-trained teachers may struggle to sustain AR usage without institutional backing due to resource constraints and a lack of ongoing support. This study corroborates their findings, emphasizing the need for professional development and structural support to ensure the sustainability of AR initiatives in education [29; 30].

The study contributes to the existing body of literature by focusing on the AR competencies of PSTE students, a relatively underexplored area. Most studies have concentrated on AR's impact on students, with limited attention to pre-service teachers' readiness and competencies [31; 33]. By addressing this gap, the study provides valuable insights into future educators' specific training and support needs. This contribution is crucial for developing targeted interventions to bridge the gap between technological advancements and practical classroom application.

The theoretical framework that underpins this study is rooted in the Technological Pedagogical Content Knowledge (TPACK) model developed by Santos and Castro [34]. The TPACK framework emphasizes the intersection of technology, pedagogy, and content knowledge, arguing that effective teaching with technology requires understanding how these domains interact. This study's findings illustrate the critical need for PSTE students to develop competencies across all three domains. The reported challenges with technical difficulties and insufficient training highlight gaps in the technological knowledge component [35; 36]. At the same time, the positive impacts on engagement and understanding underscore the potential of well-integrated AR to enhance pedagogical and content delivery.

Furthermore, the findings support Rogers' [37] Diffusion of Innovations theory, which suggests that the adoption of new technologies follows a predictable pattern influenced by factors such as perceived advantages, compatibility with existing practices, and complexity. The observed challenges in this study align with Rogers' assertion that complexity can hinder adoption. The need for targeted professional development and institutional support is crucial for simplifying the integration process and enhancing the perceived compatibility and advantages of AR in educational settings.

In conclusion, while the study reaffirms the significant benefits of AR in enhancing student learning outcomes, it also highlights the substantial challenges related to training, technical difficulties, and resource accessibility. Addressing these issues through targeted professional development and improved resource allocation will be essential for maximizing AR's potential in education. This study thus provides a critical foundation for future research and policy development to integrate AR more effectively into teacher education programs. The combination of hands-on training, continuous support, and adequate resources will be key to overcoming the challenges and fully leveraging the potential of AR in education.

CONCLUSION

This study provides valuable insights into the current state of AR competencies among PSTE students and the challenges they face in integrating AR into teaching practices. While AR shows promise in enhancing student engagement and understanding, particularly for complex concepts, significant barriers exist in its implementation. The study's limitations include its focus on a single institution and potential self-reporting bias in surveys. Future research should explore the longitudinal effects of AR integration, assess the impact of targeted professional development programs, and investigate AR's effectiveness across diverse educational contexts and subject areas. The findings underscore the critical need for comprehensive training programs, ongoing technical support, and improved access to AR resources in teacher education. By addressing these challenges, educational institutions can better prepare future educators to leverage AR technology effectively, ultimately enhancing the quality of primary education in an increasingly digital world.

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