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Virtual Reality and Mathematics Anxiety in Prospective Elementary School Teachers: A Quasi-Experimental Mixed-Methods Study

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Abstract. This study investigates the effectiveness of Virtual Reality (VR) as an educational technology in reducing mathematics anxiety among prospective elementary school teachers, distinguishing between the dimensions of academic anxiety and pedagogical anxiety. Adopting a quasi-experimental mixed methods design with an explanatory-sequential model, eighty-two prospective elementary school teachers (experimental n = 40; control n = 42) completed six intervention sessions over approximately three weeks using either the immersive VR platform MathemaVerse 3D or conventional lecture-based instruction. The experimental group showed significant reductions in both Mathematics Academic Anxiety ($\Delta = -1.11$, $t(39) = 9.25$, $p < .001$, Cohen's $d = 1.45$) and Mathematics Pedagogical Anxiety ($\Delta = -1.08$, $t(39) = 8.76$, $p < .001$, $d = 1.38$), while the control group showed no significant change. Qualitative analysis through stimulated recall interviews identified an enhanced sense of control, a safe-to-fail environment, and emotional engagement as

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key mechanisms underlying anxiety reduction. The VR intervention operated through progressive scaffolding and immersive environments, which increased perceived control, reinforced embodied cognition, and built teaching self-efficacy. This study contributes theoretically by differentiating between two dimensions of matheamtics anxiety and proposing the Anxiety-Informed TPACK Framework; while practically providing techno-pedagogical design guidelines for teacher education The findings affirm VR's role in supporting SDG 4 (Quality Education) by promoting inclusive and equitable learning opportunities for prospective teachers.

Keywords: academic anxiety; embodied cognition; inclusive education; mathematics anxiety; teacher training; pedagogical anxiety; pre-service teachers; quality education; virtual reality; educational environment

1. Introduction

1.1 Research Background

Global education is currently undergoing a major transformation marked by the acceleration of digital technology utilization (Rof et al., 2022). Educational technology is no longer merely considered as a supporting tool, but as a catalyst to create more effective, adaptive, and inclusive learning experiences (Chukwuemeka & Garba, 2024; Hendriyanto, Suryadi, Sahara, et al., 2024; Muhaimin et al., 2023, 2025). Within this framework, Virtual Reality (VR) holds a uniquely strategic position due to its capacity to provide deeply immersive experiences that are unattainable through conventional or non-immersive platforms (Angra & Jangra, 2025; Azevedo et al., 2021; Bailenson, 2018; Jawarneh et al., 2023; Lawson & Mayer, 2025; Leong, 2024, 2025; Makransky & Petersen, 2021; Pahmi et al., 2024).

By enabling students to interact directly with complex conceptual representations (Guzsvinecz et al., 2022) and sophisticated simulated environments (Ismail et al., 2024), VR fosters a sense of presence and emotional engagement that clarifies abstract concepts often difficult to grasp through traditional methods (Kim & Biocca, 2018). By offering a sense of presence and emotional engagement, VR has the potential to reduce learning barriers (Standen & Brown, 2006), increase motivation (Kim & Biocca, 2018), and strengthen the understanding of abstract concepts that are often difficult to grasp through traditional methods (Kim & Biocca, 2018).

Beyond conceptual clarity, VR holds a uniquely strategic position in this study for its ability to create a psychologically safe environment essential for mitigating mathematics anxiety (Angra & Jangra, 2025; Guinong & Yie, 2026; Standen & Brown, 2005). By providing a controlled, low-stakes simulation—an affordance often described as 'safe failure'—VR allows pre-service teachers to engage in pedagogical challenges without the immediate social pressure of a real classroom (Guinong & Yie, 2026; Lamb & Etopio, 2020). This emotional regulation mechanism serves as the core investigative focus, examining how the reduction of environmental stressors through VR facilitates a significant decrease in both academic and pedagogical anxiety. Furthermore, VR aligns with the principles of inclusivity and equity by democratizing access to high-quality experiential learning (Leong, 2025). It ensures that students with high anxiety levels, who are often disadvantaged in traditional high-pressure settings, have an equal opportunity to build competence and confidence through personalized and distraction-free learning experiences (Lawson & Mayer, 2025; Pardini et al., 2022).

The need for such innovative interventions is urgent, considering that one of the major challenges in mathematics education is the phenomenon of mathematics anxiety (Buckley et al., 2016; Hendriyanto et al., 2023; Hendriyanto, Suryadi, Juandi, et al., 2024). Mathematics anxiety is defined as feelings of fear, tension, or worry that arise when students face mathematical activities (Caviola et al., 2019; Dowker et al., 2016), whether in learning, assignments, or academic evaluations. International research, including PISA reports (OECD, 2019a), shows the high prevalence of mathematics anxiety across countries, including in Asia, which has implications for decreased performance, reduced motivation, and a tendency for students to avoid STEM-related fields. This condition highlights that mathematics anxiety is a significant global issue.

Recent studies affirm that mathematics anxiety cannot be viewed as a single phenomenon, but rather has more specific categories, especially in the context of teacher education. Pahmi, Priatna, Suhendra, & Martadiputra (2025) show that prospective teachers not only experience anxiety when they are learning mathematics, but also when they have to teach mathematics to others. In this context, there are two different yet interrelated forms of anxiety, namely mathematics academic anxiety and mathematics pedagogical anxiety.

Mathematics academic anxiety refers to the anxiety that arises when prospective teachers are studying or completing mathematics tasks (Pahmi, Priatna, Suhendra, Martadiputra, et al., 2025). This form of anxiety is often related to a lack of confidence in understanding concepts, fear of facing exams, and worry about getting poor academic results (Chakraborty, 2023; Tin et al., 2024). This condition is rooted in weak mastery of content knowledge and can significantly impair working memory and cognitive processing, both of which are critical for effective learning and teaching (Maloney & Beilock, 2012; Ramirez et al., 2018).

Moreover, international assessments such as the Programme for International Student Assessment (PISA) consistently report high levels of mathematics anxiety worldwide, linking it to decreased motivation and the avoidance of STEM-related careers (OECD, 2019b). Crucially, studies show that anxiety among prospective teachers negatively affects their teaching self-efficacy and instructional quality, which can inadvertently transmit negative attitudes toward mathematics to their future students (Beilock et al., 2010). These findings underscore the urgent need to address mathematics anxiety early in teacher education to improve both teacher readiness and student outcomes.

Conversely, mathematics pedagogical anxiety arises when prospective teachers are in the position of teaching mathematics (Pahmi, Priatna, Suhendra, & Martadiputra, 2025). This type of anxiety includes the fear of being unable to explain concepts clearly, anxiety when unable to answer students' questions, and pressure in managing classroom dynamics. This form of anxiety is closely related to limitations in the mastery of pedagogical knowledge required to deliver material effectively (Chakraborty, 2023). Both forms of anxiety do not stand alone but rather reinforce each other. Prospective teachers who have difficulties in understanding concepts also tend to feel uncertain about their abilities when teaching (Novikasari et al., 2024). Thus, the differentiation between mathematics academic anxiety and mathematics pedagogical anxiety becomes crucial, as it provides a more comprehensive picture of the challenges faced by prospective teachers in preparing themselves as mathematics educators.

However, the literature review shows a research gap. Most studies on the use of VR in mathematics education tend to focus on academic dimensions, such as test achievement (Su et al., 2022; Yu & Xu, 2022), conceptual understanding (Çakıroğlu et al., 2024), or learning motivation (Jiang & Fryer, 2024), while neglecting pedagogical aspects that include learning experiences, teacher-student interactions, and psychological comfort in participating in class. Yet, to comprehensively understand VR's effectiveness, it is essential to analyze its contribution to both dimensions separately and how they interact in addressing mathematics anxiety.

1.2 Research Objectives and Theoretical Framework

This study aims to investigate the effectiveness of VR as an educational technology in managing mathematics anxiety by distinguishing between its academic and pedagogical dimensions. Specifically, the research focuses on three main objectives. First, to empirically assess how VR-based immersive experiences reduce mathematics academic anxiety through enhanced spatial visualization, multimodal enrichment, and decreased intrinsic cognitive load. Second, to examine the impact of VR affordances—such as virtual classroom simulations, interactive avatars, and real-time feedback—on reducing mathematics pedagogical anxiety by strengthening pedagogical self-efficacy, improving perceived teaching competence, and alleviating affective tension during concept explanation practice.

Third, to explore the dynamic interaction between academic and pedagogical anxiety by positioning VR as both a mediating and moderating factor, thereby providing a holistic understanding of how VR contributes to the professional readiness of prospective mathematics teachers. By providing structured guidance that is gradually removed as competence increases, scaffolding allows learners to build 'mastery experiences' (Bandura & Watts, 1996), which are essential for lowering affective barriers and enhancing self-efficacy. Complementarily, the safe-to-fail environment provides a psychologically secure space for experimentation without social consequences, reinforcing the affective benefits of scaffolded learning.

It is essential to recognize that prospective teachers in this study are adults who have accumulated approximately 15 years of mathematics-related experiences, including deeply entrenched anxiety schemas. Unlike younger learners, these participants bring what Mezirow (2000) terms 'meaning perspectives'—habitual frames of reference that filter new experiences through existing beliefs and emotional responses. Adult learning theory Knowles et al. (2015) further suggests that adults' self-directed learning orientation may interact differently with VR's structured scaffolding than the teacher-directed approaches typical of K-12 interventions. While our findings suggest that VR's safe-to-fail environment can serve as a 'disorienting dilemma' that initiates schema revision, we acknowledge that a six-session intervention may address surface-level anxiety responses without fully restructuring deep-seated affective schemas. Longitudinal follow-up research is needed to determine whether the observed reductions persist beyond the intervention period and whether they transfer to actual classroom teaching contexts.

To achieve these objectives, the study is built on four complementary theoretical foundations. First, embodied cognition argues that mathematical understanding deepens when learners "experience" the concepts physically—even in digital representation—because rich sensorimotor interactions facilitate the construction of new schemas (Karantzoulis et al., 2021). In this study, embodied cognition justifies the use of VR tasks that concretize abstract mathematical relations (e.g., spatial visualization and manipulable models); by making concepts experientially accessible, VR aims to strengthen content mastery and thereby reduce academic anxiety that stems from conceptual uncertainty.

Second, the control–value theory of achievement emotions Pekrun (2019) explains that emotions, including anxiety, are shaped by learners' perceived control over and value assigned to tasks; VR is predicted to increase perceived control through high interactivity, immediate feedback, scaffolded difficulty, and a sense of agency (the "safe-failure" affordance), all of which alter appraisal processes and can downregulate anxiety during learning and microteaching. We operationalize this link by measuring changes in anxiety alongside participant reports of perceived control and emotional experience.

Third, the Technological Pedagogical Content Knowledge (TPACK) framework (Mishra & Koehler, 2006) stresses the importance of synergy between content, pedagogy, and technology; we extend TPACK by explicitly incorporating an affective dimension—an "anxiety-informed TPACK"—to interpret how VR-enabled pedagogical practices influence pedagogical self-efficacy and classroom-related anxiety. Finally, the study incorporates the instructional design principles of progressive scaffolding and the safe-to-fail environment. Progressive scaffolding ensures a gradual transition from guided support to independent mastery (Nachowitz, 2018), while the safe-to-fail environment provides a psychologically secure space for experimentation without social consequences (Wang et al., 2024), both of which are essential for mitigating affective barriers and building self-confidence.

The Anxiety-Informed TPACK Framework extends the Technological Pedagogical Content Knowledge model Mishra & Koehler (2006) by integrating an affective dimension—specifically, the systematic consideration of learner anxiety—into the intersection of technology, pedagogy, and content. It posits that effective technology integration in anxiety-prone domains requires not only content-appropriate technological tools and sound pedagogy, but also deliberate design for anxiety mitigation through features such as safe-to-fail environments, progressive scaffolding, and real-time affective feedback. In this framework, the 'anxiety-informed' overlay modifies each TPACK intersection: Technological Content Knowledge must address anxiety-triggering content representations; Technological Pedagogical Knowledge must incorporate anxiety-aware instructional strategies; and Pedagogical Content Knowledge must account for the affective barriers that inhibit content engagement.

Additionally, the study draws on Self-Efficacy Theory (Bandura & Watts, 1996), which highlights the role of mastery experiences, vicarious learning, and social persuasion in building confidence. VR's scaffolded microteaching simulations provide repeated mastery experiences that enhance teaching self-efficacy, thereby reducing pedagogical anxiety. Moreover, Cognitive Load Theory (Sweller, 1988) informs the design of VR learning environments by emphasizing the reduction of intrinsic cognitive load through multimodal and immersive representations. By offloading complex spatial reasoning to visuospatial channels, VR frees working memory resources, facilitating deeper conceptual understanding and lowering anxiety related to cognitive overload.

While the preceding analysis highlights CLT-aligned benefits, it is essential to acknowledge that Cognitive Load Theory also predicts conditions under which multimedia environments can impair learning. The redundancy effect occurs when identical information is presented simultaneously in multiple formats (e.g., on-screen text duplicating narration), forcing learners to process the same content twice and increasing extraneous cognitive load (Mayer, 2024; Sweller, 2011). The split-attention effect arises when learners must mentally integrate spatially or temporally separated information sources. In immersive VR environments, both risks are amplified by the richness of the sensory input.

MathemaVerse 3D's design attempted to mitigate these effects through progressive scaffolding—introducing one information channel at a time and avoiding simultaneous narration with on-screen text. However, this mitigation was a design intention rather than an empirically isolated variable. The current study did not include direct measures of extraneous cognitive load (e.g., secondary-task performance or subjective load ratings), which limits our ability to confirm that the observed anxiety reductions were not partially offset by increased cognitive processing demands. Future iterations of MathemaVerse 3D should incorporate real-time cognitive load assessment to disentangle facilitative from debilitative effects of VR immersion.

1.3 Research Questions and Hypotheses

This study investigates the transformative potential of VR in addressing the dual dimensions of mathematics anxiety—academic and pedagogical—among prospective elementary school teachers. The research is guided by two primary questions: (1) Is a Virtual Reality-based intervention significantly more effective than conventional methods in reducing mathematics academical anxiety? and (2) Is a Virtual Reality-based intervention significantly more effective than conventional methods in reducing mathematics pedagogical anxiety? To address these questions, two central hypotheses are formulated. First, it is hypothesized that the Virtual Reality intervention group will exhibit a significantly greater reduction in Mathematics Academic Anxiety (MAA) compared to the control group. Second, the research posits that the Virtual Reality intervention group will exhibit a significantly greater reduction in Mathematics Pedagogical Anxiety (MPA) compared to the control group.

1.4 Study Uniqueness, Challenges, and Practical Implications

The uniqueness of this study lies in its explicit differentiation of two domains of anxiety and cross-level variable analysis. Most previous research aggregated anxiety as a single construct, failing to detect specific variances in academic and pedagogical domains. Critically, this study also discusses the limitations and challenges of VR implementation in educational institutions—including device access, network infrastructure readiness, digital inequality across regions, risks of cybersickness, and ethical considerations regarding biometric data privacy.

These issues are often overlooked but are crucial for program sustainability and benefit equity. Additionally, this article highlights possible side effects: overly realistic VR may increase anxiety for some individuals due to overstimulation, and may raise extraneous cognitive load if instructional design does not follow multimedia learning principles (Alpizar et al., 2020). Therefore, this research not only promotes VR as a solution but also offers a critical evaluation framework to ensure its adoption is well-directed and evidence based.

From a practical perspective, the findings are expected to provide techno-pedagogical design guidelines for VR application developers and teacher education institutions, such as recommendations for adaptive scaffolding features, immersive microteaching scenarios with layered difficulty, and monitoring dashboards based on learning analytics. From a policy perspective, the results can inform national-level teacher training and technology literacy programs, emphasizing that mathematics anxiety interventions must target both content mastery and teaching competence. By integrating cognitive, affective, and pedagogical perspectives, this article is expected not only to enrich the discourse on the use of VR in mathematics education but also to propose a new conceptual framework to better understand, measure, and intervene in mathematics anxiety in a sharper and more contextual manner.

2. Materials and Methods

2.1 Research Design and Paradigm

This study is built upon a pragmatic paradigm, which emphasizes the utility of scientific knowledge in addressing concrete educational problems. Rather than being confined to the dichotomy between positivism—which stresses statistical objectivity—and constructivism—which stresses subjective experience, the pragmatic paradigm allows the integration of both by viewing truth as something tested through practical consequences (Creswell & Plano Clark, 2018). In the context of this research, the main question is not only whether VR is effective in reducing mathematics anxiety, but also how VR's immersive experience mechanisms can shape conceptual understanding while reducing both academic and pedagogical anxiety among prospective teachers.

To answer these questions, the study employed a quasi-experimental mixed methods design with an explanatory-sequential model. The quantitative approach was first used to measure changes in mathematics academic anxiety (MAA) and mathematics pedagogical anxiety (MPA) through a pretest–posttest control group design. This quantitative data was later enriched through a qualitative approach with reflective interviews based on stimulated recall, aimed at providing complementary explanations for the statistical patterns found. This sequential pattern aligns with the pragmatic paradigm, as it positions quantitative and qualitative data not as opposites, but as complementary entities to produce holistic and practical conclusions.

Technically, this quasi-experimental design was realized in two groups that were not fully randomized (non-equivalent groups). The experimental group received an intervention using an immersive VR application (MathemaVerse 3D) designed specifically to support mathematics learning through abstract concept visualizations, virtual classroom simulations, and microteaching practice with adaptive feedback. In contrast, the control group participated in learning based on conventional media, such as slides, 2D videos, and group discussions of equivalent duration. Each group underwent six intervention sessions, with a duration of approximately 100 minutes per session.

The control group received conventional instruction consisting of lecture-based sessions on the same plane and solid geometry content, supplemented with textbook exercises and traditional whiteboard demonstrations. No digital simulation or immersive technology was used. Both groups received instruction from the same instructor team, followed an equivalent content schedule over six sessions, and completed identical pre- and post-test instruments.

2.2 Participants and Setting

The research subjects were undergraduate students in elementary school teacher education programs, at middle levels of study (semesters 4–6), at a private university in Indonesia. Data collection took place during the 2nd to 4th weeks of February 2025, corresponding to the even semester of the 2024/2025 academic year. A total of 82 participants were recruited, consisting of the experimental group (n=40; M=23.80, SD=3.01) and the control group (n=42; M=23.73, SD=2.70).

The overall mean age of the participants was 23.76 years (SD=2.86). Selection was conducted using purposive sampling based on the criteria: (1) completion of at least two mathematics content courses, (2) limited teaching practice experience for 1 semester (6 months), and (3) no prior use of VR in formal learning. To minimize selection bias, matching processes were performed based on GPA, pretest anxiety scores, and demographic profiles. The experimental group included 80% females and 20% males, while the control group had 78.6% females and 21.4% males. There were no significant differences between groups in gender distribution, age, or GPA (all $p > .05$), indicating comparable baseline characteristics.

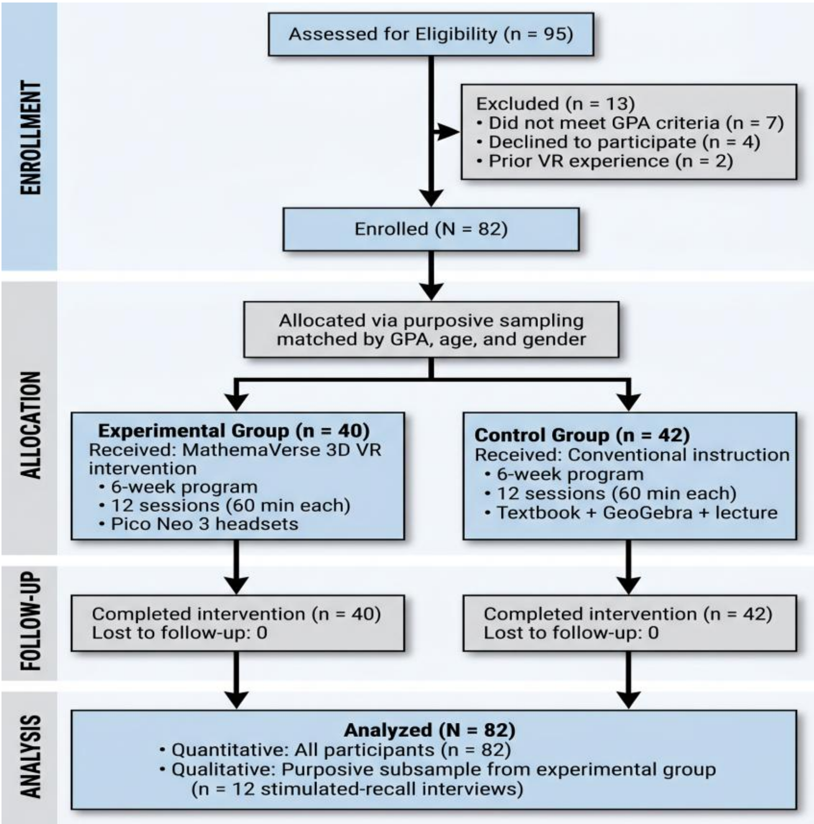


Figure 1: Participant flow diagram

As part of a commitment to inclusive education, subject selection and intervention design were aimed at representing participant diversity (Benítez-Lugo et al., 2021). Considerations were given to variations in academic ability, teaching experience, and demographic backgrounds, with the aim of ensuring that the VR-based intervention could be tested in a more egalitarian context. Moreover, the VR application design supported equal learning opportunities through adaptive scaffolding features tailored to participants' needs, aligning with SDG 4: Quality Education, which emphasizes equal access and sustainability in innovative learning models.

Given the sample size (N = 82), this study is positioned as a quasi-experimental pilot. While the large effect sizes observed (Cohen's $d > 1.3$) suggest adequate statistical power for the primary comparisons, readers should interpret the findings with appropriate caution regarding generalizability to larger and more diverse populations of pre-service teachers.

Figure 1. CONSORT-style participant flow diagram showing enrollment, allocation, intervention delivery, and analysis in the quasi-experimental study. The experimental group (n = 40) received a 6-week MathemaVerse 3D virtual

reality intervention using Pico Neo 3 headsets, while the control group (n = 42) received conventional instruction using textbooks, GeoGebra software, and lecturer-led demonstrations. No participants were lost to follow-up. Qualitative data were collected from a purposive subsample of 12 experimental participants via stimulated-recall interviews.

2.3 Research Instruments

The main quantitative data collection instruments consisted of the Mathematics Academic Anxiety Scale (MAAS-PT) and the Mathematics Pedagogical Anxiety Scale (MPAS-PT). Each scale comprises 30 items designed to measure academic and pedagogical anxiety respectively. Both instruments employed a semantic differential scale with a score range from 0 to 10, allowing respondents to provide specific evaluations of each aspect being assessed (Osgood et al., 1957). Sample items from the MAAS-PT include statements such as "I feel nervous when solving math problems," while the MPAS-PT includes items like "I feel anxious when planning math lessons."

For the qualitative phase, a semi-structured interview protocol was developed based on the same four-dimensional framework of mathematics anxiety (cognitive, affective, physiological, and behavioral) used in the quantitative instruments (Chand & Marwaha, 2023). This approach allowed for a deeper exploration of how these dimensions manifested during the VR experience. The procedure followed a structured sequence: (1) immediately after the VR session, participants were shown key segments of their recorded performance, (2) the researcher paused the video at critical decision-making points or moments of high interaction, and (3) participants were asked to describe their internal thought processes and emotional states at those specific moments (Lyle, 2003).

The validity and reliability of the quantitative instruments, specifically the MAAS-PT and MPAS-PT scales, were established through a rigorous development process based on the four dimensions of mathematics anxiety: cognitive, affective, physiological, and behavioral (Chand & Marwaha, 2023). These scales had previously undergone testing for construct validity and internal reliability, yielding high Cronbach's alpha coefficients of 0.89 and 0.91, respectively, which confirms their consistency in measuring academic and pedagogical anxiety.

For the qualitative phase, the validity of the semi-structured interview guide was ensured through a formal validation process involving a panel of experts specializing in psychology, linguistics, and educational research. This panel assessed the instrument for content relevance, linguistic clarity, and alignment with the research objectives, ultimately categorizing the guide as valid for capturing nuanced qualitative data. Furthermore, the reliability of the qualitative coding process was maintained by assessing inter-rater reliability. Cohen's kappa was calculated based on a subset of 20% of the transcripts coded independently by two researchers, resulting in a value of 0.82. This score indicates substantial agreement between coders and confirms the objectivity and reliability of the thematic analysis conducted on the interview data.

To maintain internal validity, the study applied monitoring of treatment fidelity through system logs and data triangulation by presenting a joint display matrix that integrated quantitative findings, activity logs, and qualitative narratives. The analysis of system logs confirmed high treatment fidelity, with participants in the experimental group completing an average of 92% of the VR modules and spending an average of 45 minutes (SD = 5.4) per session. These logs were cross-referenced with posttest scores, revealing a significant correlation between the frequency of interaction with VR feedback and the reduction in pedagogical anxiety (r = -0.42, p < .01). Furthermore, the joint display matrix allowed for a nuanced interpretation of the results, showing that participants who exhibited high engagement in the logs also reported more profound cognitive shifts during stimulated recall interviews.

2.4 Data Analysis Procedures

Quantitative data from the questionnaires were analyzed using SPSS version 26.0. The analysis began with descriptive statistics to summarize the mean scores and standard deviations for both Mathematics Academic Anxiety (MAA) and Mathematics Pedagogical Anxiety (MPA) across groups. To ensure the comparability of the two groups at baseline, independent samples t-tests were conducted to assess sample equivalency. This analysis confirmed that there were no significant differences between the experimental and control groups in terms of academic achievement (GPA), age, or initial anxiety levels ($p > .05$), indicating that both groups started from a comparable baseline. Prior to conducting parametric analyses, Shapiro-Wilk tests were performed to assess the normality of pretest and posttest score distributions for both MAA and MPA across both groups. Results confirmed that all distributions were approximately normal (all p > .05), supporting the use of paired and independent samples t-tests.

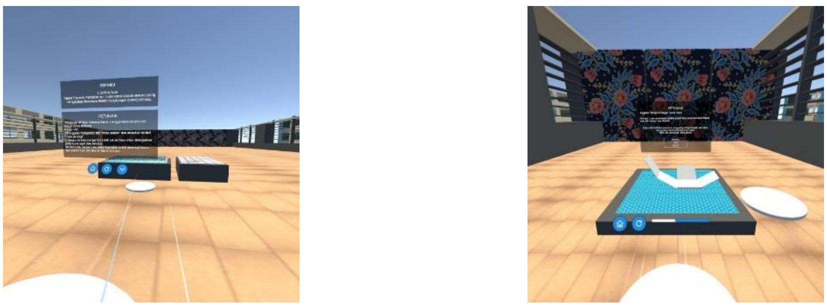
To examine changes in anxiety scores from pretest to posttest within each group, paired t-tests were conducted. Additionally, independent samples t-tests were employed to compare the mean gain scores between the experimental and control groups, ensuring a rigorous evaluation of the intervention's relative effectiveness. Prior to the main analysis, the assumption of normality was verified using the Shapiro-Wilk test, which confirmed that the data followed a normal distribution ($p > .05$). The homogeneity of variance was also assessed and confirmed using Levene's test. To determine the practical significance of the findings, effect sizes were calculated using Cohen's $d$for t-tests and partial eta squared (η^2) for group comparisons. These metrics provided a standardized measure of the magnitude of the intervention's impact, beyond mere statistical significance. Regarding missing data, there were no missing values (0%) as the digital questionnaire system required all items to be completed before submission, ensuring the integrity and completeness of the dataset for all 82 participants.

For the qualitative data analysis, a manual thematic analysis was conducted on the stimulated recall interview transcripts following the systematic approach outlined by Braun & Clarke (2006). The analysis began with familiarization, where two researchers independently read and re-read all interview transcripts to gain a comprehensive understanding of the data. This was followed by an initial open coding phase, during which meaningful units of text (codes) were identified and labeled based on participants' expressions of anxiety experiences and their interactions with the VR environment. Codes were generated both inductively from the data and deductively based on the four-dimensional anxiety framework (cognitive, affective, physiological, and behavioral). The axial coding phase involved organizing the initial codes into broader categories and emergent themes. An a priori coding framework was developed based on the theoretical constructs of mathematics anxiety, which was then refined inductively as new patterns emerged from the data. This hybrid approach ensured both theoretical grounding and openness to novel insights from participants lived experiences.

To ensure analytical rigor and trustworthiness, two independent coders (the second and third authors) performed the coding process separately. Both coders had extensive training in qualitative research methods and were familiar with the study's theoretical framework. Discrepancies between coders were documented and resolved through structured discussion meetings until consensus was reached on all coded segments. The final phase involved reflexive thematic analysis, where the research team engaged in critical reflection to interpret how the identified themes related to the research questions and theoretical frameworks. Representative quotes were selected to illustrate key findings and ensure transparency in reporting. The themes were then integrated with quantitative results and system log data through a joint display matrix to provide a comprehensive, triangulated interpretation of how VR mechanisms contributed to anxiety reduction.

2.5 Mechanisms of VR Intervention

To comprehensively understand how Virtual Reality (VR) significantly reduced Mathematics Academic Anxiety (MAA) and Mathematics Pedagogical Anxiety (MPA), it is important to describe the underlying intervention mechanisms. This section details the design and implementation of VR interventions, highlighting specific features that contributed to participants’ psychological changes and linking them to relevant theoretical frameworks. Thus, VR can be seen not only as a learning tool but as a structured, adaptive learning environment that systematically targets the root causes of mathematics anxiety. Integrating VR into learning facilitates abstract material in mathematics, such as 2D and 3D geometry. A VR visualization in this case can be seen in Figure 2.



(a) (b)

Figure 2: Visualization in the VR environment on the topic of plane and solid geometry

The VR-based intervention specifically targeted plane and solid geometry, a core component of the elementary mathematics curriculum that often triggers high anxiety due to its abstract spatial requirements. The learning content covered fundamental concepts including the properties of polygons, area and volume calculations, spatial visualization of 3D objects, and the pedagogical strategies for teaching these topics to elementary students. This was enabled by specific VR affordances: (1) spatial immersion, allowing participants to walk around and 'enter' 3D geometric shapes to understand internal properties; (2) real-time manipulation, where participants could deconstruct 3D solids into 2D nets; and (3) simulated microteaching, where they practiced explaining these concepts to virtual student avatars.

In contrast, the control group engaged with the same geometric topics using conventional methods, which included 2D PowerPoint presentations, physical manipulatives (paper models), and traditional face-to-face peer microteaching. While the content was identical, the control group lacked the immersive visualization and the 'safe-to-fail' virtual environment provided by the VR system. The intervention for both groups was designed in six learning sessions, each lasting approximately 100 minutes, following a progressive sequence (see Table 1).

Table 1: Sequence of VR intervention sessions, instructional focus, and targeted anxiety reduction

Session	Intervention Focus	Core Activities	Targeted Anxiety
1	Exploration of basic concepts (academic focus)	3D visualization, plane and solid figures → object manipulation	Reduce academic anxiety related to misconceptions
2	Independent problem-solving simulation	Mathematical problem exercises with adaptive scaffolding	Reduce fear of failure in problem-solving
3	Basic microteaching (pedagogic focus)	Prospective teacher explains simple math operations to student avatar	Reduce fear of "being unable to explain"
4	Intermediate microteaching	Interactive classroom scenario with virtual student questions	Manage verbal tension & spontaneous responses
5	Collaborative problem-solving (integration)	Classroom simulation where students solve difficult problems with peer avatars	Reduce social awkwardness & increase pedagogical control
6	Open teaching trial	Prospective teacher simulates one full session teaching a complex concept	Decrease academic & pedagogical anxiety simultaneously

During the intervention process, two instructional design principles became the main foundation in the implementation of Virtual Reality, namely progressive scaffolding and safe-to-fail environment. The principle of progressive scaffolding was applied through the sequence of six intervention sessions designed in stages. In the initial sessions, students were introduced to mathematical concepts in a simple form with fairly intensive instructional support, such as text guidance, audio narration, and step-by-step visualization. This approach provided a sense of security at the beginning stage and prevented students from being directly exposed to complex demands that could trigger anxiety.

Entering the middle sessions, the level of support was gradually reduced, while students were encouraged to be more active in constructing answers, exploring alternative solutions, and developing independent understanding strategies. In the final sessions, they were challenged to fully teach a simulated class, including facing spontaneous interactions from virtual student avatars. This gradual transition allowed students to build competence step by step, so that self-efficacy increased in line with the reduction of dependence on external assistance. Thus, scaffolding functioned not only as temporary support, but also as a psychological strengthening mechanism that progressively reduced anxiety.

The second principle is the safe-to-fail environment, namely the creation of a safe virtual learning space where mistakes bring no social or academic consequences. In VR simulations, participants could try various approaches without worrying about negative evaluation from lecturers or peers. If errors occurred, the system provided real-time feedback in the form of highlighted incorrect answers, brief correction cues, or neutral responses from avatars. This enabled students to perceive mistakes not as failures, but as an integral part of the learning process. In this way, the learning experience became more reflective and supported the formation of stronger metacognitive strategies.

The combination of progressive scaffolding and safe-to-fail environment proved to create an immersive, inclusive, and adaptive learning environment. Students not only experienced improvement in conceptual understanding, but also an affective shift toward greater self-confidence. This clarifies the mechanism through which VR reduces mathematics anxiety, both in academic and pedagogical domains. The process of reducing mathematics anxiety through VR interventions does not occur instantly but rather operates through complex and interrelated psychological mechanisms. Analysis of quantitative and qualitative results shows that the changes experienced by students are rooted in three main aspects: perception of control and value of the activity, sensorimotor engagement, and reinforcement of pedagogical self-efficacy.

First, the mechanism of reducing anxiety can be understood within the framework of Control-Value Theory of Achievement Emotions (Pekrun, 2019). This theory emphasizes that academic emotions, including anxiety, are determined by the extent to which learners feel they have control over the learning activity and value the activity as meaningful. In the context of VR, students gained interactive, flexible, and self-paced learning experiences, which increased the perception of control. Students no longer felt "forced" to follow the lecturer's pace or feared being left behind but rather were able to manage their own learning process. At the same time, the immersive nature of VR provided added value to the learning experience, as the activity felt more meaningful and realistic compared to merely listening to abstract explanations. This combination of high control and high value systematically reduced both academic and pedagogical anxiety.

Second, the findings can also be explained through the framework of Embodied Cognition. With the presence of 3D visualization, object manipulation, and integration of multimodal interaction (visual, audio, kinesthetic), students not only "saw" mathematics abstractly, but also "experienced" it sensorimotorically. This sensorimotor experience strengthened mental constructions and accelerated conceptual schema integration, thereby reducing intrinsic cognitive load. Psychologically, when students were able to build more solid understanding, the main sources of anxiety—namely feelings of uncertainty and fear of making mistakes—were minimized. In other words, embodied cognition acted as a bridge between cognitive experience and the reduction of affective burden.

Third, in the pedagogical context, the mechanism of reducing anxiety can be seen from the increase in teaching self-efficacy. Based on Bandura & Watts (1996) theory, pedagogical self-efficacy is built from mastery experiences, vicarious experiences, and verbal/social persuasion. VR provided mastery experiences progressively, from simple microteaching to complex classroom scenarios, which strengthened confidence in teaching. Interaction with neutral student avatars functioned as a safe feedback mechanism, supporting verbal/social persuasion in a non-judgmental manner. As a result, pre-service teachers became increasingly confident in their teaching capacity, which in turn reduced pedagogical anxiety.

These three mechanisms—high control & value, sensorimotor engagement, and increased pedagogical self-efficacy—worked synergistically in creating a new, more stable psychological condition. With reduced math-related anxiety, students could better focus on achieving academic and pedagogical goals and demonstrate greater professional readiness. This clarifies that the role of VR is not limited to being a medium of content delivery, but as a simulated learning environment that simultaneously targets cognitive, affective, and pedagogical dimensions. Table 2 summarizes the relationship between the design of VR intervention, psychological mechanisms, and outcome of anxiety reduction.

Table 2: Intervention components, underlying psychological mechanisms, and anxiety reduction outcomes

Intervention Component	Psychological Mechanism	Outcome
3D visualization & multimodality	Reduced cognitive load, strengthened conceptual representation (Embodied Cognition)	Academic anxiety reduced
Adaptive scaffolding	Increased perceived control (Control-Value Theory)	Academic & pedagogical anxiety reduced
Progressive microteaching simulation	Mastery experience → enhanced teaching self-efficacy	Pedagogical anxiety reduced
Safe-to-fail environment + real-time feedback	Reframing mistakes as learning → reduced social tension	Academic & pedagogical anxiety reduced simultaneously

With a progressively designed six-session structure, this VR intervention presents an integrated interplay between content, pedagogy, and technology. When analyzed through the TPACK lens, VR not only enriches content knowledge through interactive visualization, but also strengthens the pedagogical skills of prospective teachers in interacting with students, all of which are facilitated by technological affordances. This is what makes the VR intervention unique, as it positions VR not merely as a "visualization tool" for learning mathematics, but as a complete pedagogical training space that reduces both types of anxiety simultaneously (Pahmi, Priatna, Suhendra, & Martadiputra, 2025). In this way, VR serves as a catalyst for inclusive education, enabling all students—including those who are usually vulnerable to anxiety—to fully participate in quality learning opportunities.

2.6 Virtual Reality Platform

Hardware: The experimental group used Pico Neo 3 Pro all-in-one VR headsets (Qualcomm Snapdragon XR2 processor; 6 GB RAM; dual 2160 × 2160 LCD displays per eye; 90 Hz refresh rate; 98° field of view). The standalone design eliminated the need for external PCs or tracking stations, allowing flexible deployment across multiple training rooms. Each participant was fitted with adjustable head straps and interpupillary distance (IPD) calibration (58–72 mm) to optimize visual comfort.

Software: MathemaVerse 3D was developed in-house by the first author's research team using Unity 2021.3 LTS (Unity Technologies, 2021) as the core game engine, with the XR Interaction Toolkit for controller input and the Pico SDK 2.2 for hardware integration. The application was compiled as an Android APK and sideloaded onto each headset via Pico Developer Mode.

Design Features: The virtual environment simulates a three-dimensional geometric workspace where prospective teachers manipulate polyhedra, spatial transformations, and cross-sections using hand-tracked gestures. Adaptive scaffolding algorithms (written in C#) adjust task complexity based on real-time performance metrics (error rate, time-on-task). The prototype is currently a research tool and not publicly distributed, though access may be granted to peer researchers for replication studies upon formal request.

3. Result and Discussion

This study involved 82 prospective elementary school teachers divided into an experimental group (n = 40) and a control group (n = 42). Both groups participated in six learning intervention sessions. The instruments used included the Mathematics Academic Anxiety Scale (MAAS-PT) and the Mathematics Pedagogical Anxiety Scale (MPAS-PT) to measure participants' anxiety levels before and after the intervention.

Table 3: Summary of statistical results

Variable	Group	Pretest (M ± SD)	Posttest (M ± SD)	Δ Mean	t / F	p-value	Effect Size (Cohen's d)	Partial η^2
MAAS (Academic Anxiety)	Experimental (n = 40)	3.82 ± 0.54	2.71 ± 0.57	−1.11	t(39) = 9.25	< .001	1.45 (large)	0.42
	Control (n = 42)	3.79 ± 0.59	3.61 ± 0.63	−0.18	t(41) = 1.52	.136	0.21 (small)	0.02
MPAS (Pedagogical Anxiety)	Experimental (n = 40)	3.91 ± 0.61	2.83 ± 0.64	−1.08	t(39) = 8.76	< .001	1.38 (large)	0.39
	Control (n = 42)	3.95 ± 0.58	3.72 ± 0.60	−0.23	t(41) = 1.87	.068	0.29 (small)	0.03

Note: 95% confidence intervals
Source: SPSS 26

The data analysis results (Table 3) show a significant decrease in both types of mathematics anxiety in the experimental group. For Mathematics Academic Anxiety (MAA), the average student score dropped from M = 3.82, SD = 0.54 at pretest to M = 2.71, SD = 0.57 at posttest, with t(39) = 9.25, $p < .001$. This decrease produced a very large effect size (Cohen's d = 1.45, partial eta^2 = 0.42). Meanwhile, in the control group, the average decrease was not significant (M = 3.79 → 3.61; t(41) = 1.52, p = .136).

For Mathematics Pedagogical Anxiety (MPA), the experimental group also experienced a significant decrease from M = 3.91, SD = 0.61 to M = 2.83, SD = 0.64 at posttest, t(39) = 8.76, $p < .001$. The intervention effect was also large with Cohen's d = 1.38, partial eta^2 = 0.39. Conversely, the control group only showed a small and non-significant change (M = 3.95 → 3.72; t(41) = 1.87, p = .068). Overall, these findings indicate that the VR-based intervention effectively reduced both academic and pedagogical anxiety, with very large effect sizes, while the conventional approach was unable to generate similar changes.

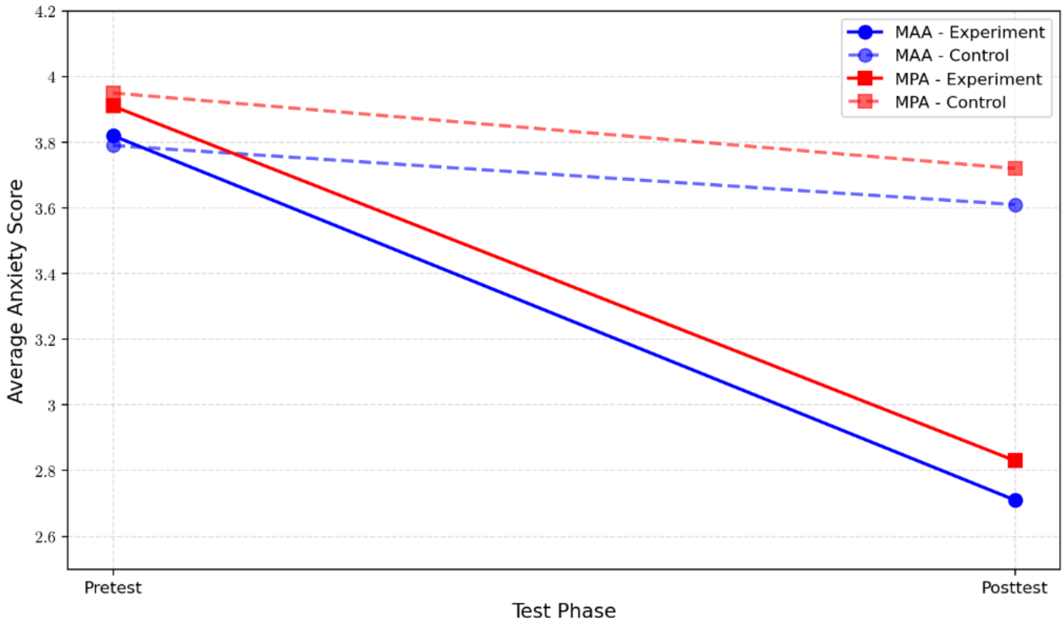


Figure 3: Trend of decrease in mathematics anxiety scores (academic and pedagogical) in experimental and control groups

Qualitative analysis based on stimulated recall interviews enriched the quantitative results by providing in-depth understanding of students' experiences. Three main themes emerged:

Increased sense of control (perceived control): Students felt more confident in understanding mathematical concepts because they could see and manipulate abstract representations in the VR environment. One participant stated, "*I used to be afraid of making mistakes when calculating fractions, but with VR I can visualize the parts directly. It makes me feel more confident*." (E23).

A safe environment for teaching practice (safe-to-fail environment): VR provided a virtual classroom simulation space where prospective teachers could try out different teaching strategies without fear of being judged by real students. This was reflected in the statement, "*I wasn't nervous like in a real class. If I made a mistake, I could try again without feeling embarrassed*." (P11).

Increased emotional engagement: The immersive experience made students more focused, motivated, and able to forget their anxiety. A participant explained, "I felt like I was really in the classroom. It made me more focused and I forgot my anxiety." (P07). The integration of quantitative and qualitative results confirms that the reduction in participants' anxiety was supported by both objective indicators and subjective experiences.

Table 4: Synthesis of quantitative and qualitative findings

Dimension	Quantitative Findings	Qualitative Findings	Interpretative Integration
Academic Anxiety (MAA)	Significant decrease Δ = -1.11, d = 1.45	3D visualization improved understanding, reduced fear of mistakes	VR reduces cognitive load and enhances learning control
Pedagogical Anxiety (MPA)	Significant decrease Δ = -1.08, d = 1.38	Virtual classroom simulations provided safety and improved self-efficacy	VR creates a safe-to-fail environment that reduces pedagogical anxiety
Affective & Motivation	Not measured quantitatively	Students reported greater focus, motivation, and emotional engagement	The immersive VR experience functions as an emotional buffer, reducing anxiety and increasing participation

Based on the integration of the two types of data, it can be concluded that the VR intervention is not only effective in reducing mathematics anxiety academically and pedagogically but also serves as a critical tool for promoting educational equity. By providing a 'safe-to-fail' environment and enhancing perceived control, VR effectively removes the affective barriers that often marginalize high-anxiety students in traditional, high-pressure classrooms. Thus, these findings affirm the relevance of VR in supporting inclusive education by ensuring that students previously disadvantaged by psychological stressors have equal access to quality learning opportunities. This alignment with SDG 4 demonstrates that technological innovation can democratize competence-building, ensuring that emotional vulnerability does not translate into academic exclusion.

From the academic aspect, the findings of this study are aligned with the framework of Cognitive Load Theory; 3-D visualization and multimodality transfer part of the processing load from verbal working memory to the visuospatial channel, thereby decreasing intrinsic load and freeing cognitive space for conceptual understanding (Sweller, 2011). At the same time, the principle of Embodied Cognition explains how sensorimotor engagement (gestures, object manipulation) strengthens mental representation, accelerates schema formation, and ultimately reduces anxiety that typically arises from conceptual uncertainty (Foglia & Wilson, 2013).

The relationship between anxiety reduction and the perception of control is also consistent with the control-value theory of achievement emotions (Pekrun, 2019). The self-paced learning mode allows students to determine their own learning rhythm, enhance their sense of agency, and suppress symptoms of academic anxiety. Practically, these results confirm that VR design focusing on concrete visualization, multimodality, and self-paced control is a prerequisite if institutions aim to maximize the affective benefits of VR in mathematics learning. Furthermore, from the perspective of pedagogical mathematics anxiety, the findings of this study can be understood through two main theoretical frameworks. First, the TPACK framework explains the importance of integrating three dimensions: content, pedagogy, and technology. In this case, VR not only presents mathematical content, but also creates a pedagogical space where pre-service teachers can hone teaching skills through interactive technology. Thus, VR strengthens the pedagogical dimension in TPACK, which is often overlooked in previous studies that predominantly focused on the academic aspect.

Second, the concept of teaching self-efficacy becomes key. VR enables pre-service teachers to build confidence through repeated experiences, direct feedback, and opportunities to teach in a risk-free environment. Bandura & Watts (1996) identifies mastery experience as the main source of self-efficacy. Through VR simulations, pre-service teachers undergo mastery experiences repeatedly—from simple tasks to complex ones—which have been proven effective in enhancing self-efficacy while reducing anxiety. The strength of these findings lies in the combination of VR affordances: immersive virtual classroom experiences, safe space for mistakes, and gradual practice. These three factors synergize to create a learning climate in which pedagogical anxiety decreases, while confidence as a teacher increases. This reinforces the contribution of VR not only in "learning mathematics," but also in preparing pre-service teachers to become effective, innovative, and inclusive educators.

It is important to acknowledge that immersive VR requires hardware investment that may not be feasible in all educational contexts, particularly in developing countries where this study was conducted. The Meta Quest 2 headsets used in this study cost approximately $300–400 USD per unit, which presents a significant barrier for under-resourced institutions. Low-cost alternatives such as smartphone-based VR viewers (e.g., Google Cardboard at <$15) or desktop-based 3D simulations could extend accessibility, although the degree to which reduced display fidelity and interaction quality affect anxiety-reduction outcomes remains an empirical question. Future research should compare the efficacy of high-fidelity immersive VR versus low-cost alternatives across diverse institutional and economic contexts to establish minimum technological thresholds for effective anxiety intervention.

A critical question raised by these findings is whether VR reduces mathematics anxiety through genuine competence development or merely suppresses anxiety symptoms through immersive distraction and novelty effects. Our outcome measures (MAAS-PT, MPAS-PT) capture proximal anxiety states but do not assess distal indicators such as mathematical content knowledge gains, actual classroom teaching performance, or student learning outcomes under these prospective teachers' instruction. It is possible that the engagement and immersion of VR temporarily mask anxiety without building the durable mathematical and pedagogical mastery that would prevent anxiety recurrence once the novelty subsides. The absence of a delayed posttest (e.g., 3–6 months post-intervention) further limits our ability to distinguish between transient suppression and lasting reduction. Future studies should include both immediate and delayed posttests alongside performance-based competence measures to address this critical distinction.

To situate these findings within the broader literature, it is instructive to consider Wu et al. (2023) recent studies that report null or mixed results for VR interventions in educational settings. For example, Mayer et al. (2023) found that immersive virtual reality did not significantly improve learning outcomes compared to less immersive desktop-based conditions, and in some cases even resulted in lower retention due to increased cognitive load and distraction. Similarly, Makransky, Petersen, and Immordino reported that while VR increased learners' sense of presence and engagement, it did not consistently translate into better learning outcomes, suggesting that immersion alone is insufficient to guarantee cognitive benefits.

Further evidence indicates that the effectiveness of VR is often moderated by individual differences. Makransky & Petersen (2019) showed that learners with higher spatial ability benefited more from immersive environments, while those with lower spatial ability experienced greater cognitive load and reduced learning efficiency. In addition, Radianti et al. (2020), through a systematic review, emphasized that prior experience with digital technologies significantly influences how learners process VR environments, with novice users being more susceptible to disorientation and cognitive overload. These findings highlight that learner characteristics such as spatial ability, technological familiarity, and anxiety profiles play a critical role in shaping the outcomes of VR based interventions.

Such contrasting evidence underscores that VR is not a universal remedy and that its effectiveness depends on careful instructional design, appropriate alignment between content and technological affordances, and sensitivity to learner characteristics. The relatively strong effects observed in the present study may therefore reflect the specific design features of MathemaVerse 3D, particularly its progressive scaffolding and safe to fail environment, rather than the inherent advantages of VR technology itself. This interpretation reinforces the argument that pedagogical design, rather than technological sophistication alone, is the primary driver of meaningful learning and anxiety reduction in immersive environments.

3.1 Critical Boundaries: When VR May Increase Cognitive Load

While results show significant anxiety reduction in both academic and pedagogical dimensions, Cognitive Load Theory warns that immersive VR is not cognitively neutral. The same affordances that create presence and embodiment, such as stereoscopic vision, spatial audio, haptic feedback, and rich 3D environments, can simultaneously create extraneous cognitive load for math anxious learners whose working memory is already compromised (Eysenck et al., 2007). Sweller (2011) and Mayer (2024) have documented that poorly designed multimedia environments trigger redundancy and split attention effects, forcing learners to expend cognitive resources on integrating disparate information channels rather than constructing mathematical schemas. In VR, these risks are amplified because learners must simultaneously process depth cues, navigate three-dimensional space, manipulate virtual objects with unfamiliar controllers, and decode mathematical representations, all while managing anxiety induced working memory constraints. Thus, the immersive fidelity of VR represents a double-edged sword that can either scaffold understanding or overwhelm cognitive architecture depending on instructional design quality.

Critically, our stimulated recall interview data provides limited evidence of such cognitive overload. Among the 12 participants selected for in depth interviews, none spontaneously reported feeling overwhelmed by visual complexity, difficulty focusing on mathematical content versus navigation demands, or sustained cognitive friction during VR sessions. Only two participants, identified as E07 and E15, mentioned brief initial disorientation during Session 1, which they described as dissipating by Session 2 once controller mechanics became automatic. This near absence of cognitive load complaints could be interpreted in two ways. First, it may validate the progressive scaffolding design of MathemaVerse 3D.

By introducing information channels sequentially and allowing learner-controlled pacing, the system may have successfully prevented extraneous load from exceeding working memory capacity. Alternatively, this finding may reflect a methodological limitation because our interview protocol did not explicitly probe for extraneous load experiences, focusing instead on affective and pedagogical dimensions. Participants may have experienced cognitive strain but lacked the metacognitive vocabulary to articulate it, or they may have attributed processing difficulty to mathematical content rather than VR interface demands. Future research should incorporate direct cognitive load measurement rather than relying on spontaneous participant disclosure.

MathemaVerse 3D attempted to mitigate cognitive overload through several evidence-based strategies, including sequential information presentation to avoid simultaneous narration and on-screen text, spatial highlighting and animated cueing to guide visual attention, learner-controlled pacing with pause and replay functions, and progressive complexity beginning with 2D polygon manipulations before advancing to 3D solid deconstructions. These features align with Mayer (2024) multimedia learning principles and the worked example effect described by Sweller (2011).

However, these design features were embedded a priori based on theoretical principles. We did not empirically isolate their contribution to load reduction through experimental manipulation. A more rigorous approach would employ a factorial design comparing scaffolded versus non scaffolded VR conditions or measuring cognitive load directly via dual task paradigms or subjective rating scales such as the Paas scale. Without such experimental isolation, we cannot definitively attribute anxiety reduction to optimized cognitive architecture versus other mechanisms such as novelty effects, distraction from anxiety provoking cues, or simple exposure desensitization. This ambiguity represents a critical gap between our design intentions and our empirical evidence.

This gap becomes more salient when we consider contrasting findings in recent VR literature. Although our study observed large effect sizes for anxiety reduction, meta-analyses suggest that the cognitive benefits of VR are mediated by instructional design kualitas rather than technological immersion per se (Radianti et al., 2020). Studies with adult learners in geometry heavy domains have reported mixed results, with some finding that high fidelity VR produced higher cognitive load ratings than traditional instruction, particularly among learners with high spatial anxiety or low prior technology experience. For instance, recent research by and more recently by Mayer et al. (2023) suggests that highly immersive 360-degree video can lead to lower learning outcomes compared to desktop alternatives due to the overwhelming nature of the sensory environment.

Our findings may diverge from such studies due to several factors, such as our six-week duration which allowed habituation to VR mechanics, our adult sample possessing higher metacognitive awareness than K 12 populations, our anxiety specific design prioritizing affective safety over sensory realism, and our progressive scaffolding preventing premature exposure to complex multi modal demands. Nevertheless, we must maintain epistemic humility. We cannot rule out that our observed anxiety reduction reflects affective distraction, which is a temporary masking of anxiety through immersive engagement, rather than genuine cognitive restructuring that would persist in non-VR contexts or transfer to actual classroom teaching performance.

Future research must directly measure extraneous cognitive load to distinguish between VR environments that reduce anxiety by optimizing cognitive architecture versus those that merely mask anxiety through technological novelty. We recommend multimodal assessment protocols including the following elements. First, secondary task reaction time paradigms utilizing dual task methodology should be used to detect working memory saturation during VR sessions. Second, subjective mental effort ratings should be administered immediately after each session using validated instruments such as NASA TLX or the Paas scale. Third, eye tracking metrics including fixation dispersion and saccade frequency should be employed as proxies for split attention and visual search difficulty. Finally, physiological indicators such as heart rate variability and electrodermal activity should be monitored, as these have been validated as cognitive load indicators in educational VR contexts.

Critically, these measures should be collected alongside anxiety scales to test the hypothesis that anxiety reduction and cognitive load follow an inverted U relationship. In this model, moderate immersion optimizes both dimensions, but excessive sensory fidelity overwhelms working memory and paradoxically increases anxiety. Only through such multimodal assessment can we distinguish between VR environments that reduce anxiety by optimizing cognitive architecture versus those that merely mask anxiety through technological novelty, ensuring that future VR interventions for math anxious populations are grounded in cognitive science rather than technological enthusiasm.

4. Implications

4.1 Educational Equity and SDG 4: Implications for Inclusive Teacher Preparation

The significant reduction in anxiety observed in the VR group (as shown in Table 3) does not merely represent a statistical gain, but a fundamental shift toward educational equity. The findings of this study carry significant implications for advancing educational inclusivity within the framework of Sustainable Development Goal 4 (Quality Education) (Colglazier, 2015). By effectively reducing both academic and pedagogical mathematics anxiety, the VR intervention fosters a learning environment that is more accessible and supportive, particularly for prospective teachers who might otherwise experience marginalization due to affective barriers. Key features of the VR system work synergistically to provide equitable opportunities for all learners. These affordances help dismantle traditional obstacles related to confidence and access to authentic practice, ensuring that diverse learner profiles can engage fully and confidently without the fear of social judgment or conceptual uncertainty.

Such outcomes resonate strongly with UNESCO's framework for inclusive education, which emphasizes the necessity of adaptive and non-discriminatory learning methods to address learner diversity (UNESCO, 2006). By alleviating anxiety, VR serves as a strategic pedagogical instrument capable of reducing educational inequalities rooted in psychological factors, ultimately preparing educators who are more confident and inclusive in their teaching approach. This study underscores that integrating VR into teacher education is not merely a technological upgrade, but a real implementation of SDG 4 that promotes long-term capacity building. Teachers with lower anxiety levels are better equipped to foster equitable classrooms, creating a positive ripple effect that supports the global mandate for quality education for all.

4.2 Practical Implications

The findings of this study have a number of significant practical implications for stakeholders in the education ecosystem, ranging from prospective teacher students, teacher education institutions, educational technology developers, to policymakers. By reducing mathematics anxiety both academically and pedagogically, the VR intervention shows real potential to be transformed into practice, innovation, and broader educational policy.

For prospective teachers, the use of VR as a learning medium and microteaching practice offers a safe space to sharpen pedagogical competencies without social or academic pressure. Students can repeat practice sessions as many times as needed, experiment with teaching methods, and receive direct feedback, which in real classrooms is often difficult to achieve. Thus, VR can function as a pedagogical laboratory for prospective teachers. This not only reduces anxiety but also increases teaching self-efficacy and professional readiness before entering field practice. For technology developers, this study presents design guidelines for VR features effective in reducing math anxiety. Several key features that need to be prioritized are:

- Progressive scaffolding → introducing concepts gradually from simple to complex.
- Safe-to-fail environment → allowing users to trial & error without negative emotional consequences.
- Real-time feedback & analytics → a system that provides immediate feedback while recording user engagement log data for further evaluation.

By integrating these features, developers can produce VR products that not only facilitate learning by seeing but also learning by doing in a risk-free space. In addition, the concept of adaptive VR based on learning analytics can be further developed to accommodate highly diverse learning needs, in line with the vision of personalized learning. From a macro perspective, the results of this study are relevant for teacher digital literacy strengthening policies, especially in developing countries. Governments and higher education institutions can make use of VR as a tool for teacher education reform through:

- Integration of VR into teacher education curricula as a complementary alternative to traditional microteaching.
- Tiered teacher training programs that not only focus on content, but also affective aspects related to stress and anxiety.
- Reducing disparities in teacher training quality across regions through the distribution of standardized VR modules, so that students in areas with limited access can also gain equal learning experiences as those in big cities.

Furthermore, the adoption of VR at the policy level can be positioned as a tangible manifestation of the implementation of SDG 4 (Quality Education – inclusive & equitable learning opportunities), because this technology directly reduces psychological barriers, provides an inclusive practice space, and ensures fair learning opportunities for all prospective teachers regardless of background. By bringing together the perspectives of practice (prospective teachers), innovation (edutech developers), and policy (national education), this study asserts that VR is not merely a learning aid but a strategic instrument to prepare educators who are more confident, competent, and inclusive. Its multiplicative effect can be felt in elementary classrooms, where children will learn from teachers who are low in anxiety, innovative, and embracing diversity.

Table 5: Practical Guidelines for Stakeholders

Stakeholder	Guideline	Priority	Evidence
Pre-service Teachers	Use VR microteaching simulations for repeated low-stakes practice before real classroom exposure.	High	Qualitative theme: safe-to-fail environment reduced pedagogical anxiety.
Teacher Education Institutions	Integrate 4–6 session VR modules into methods courses, targeting both academic and pedagogical anxiety.	High	Six sessions produced Cohen's d > 1.3 for both anxiety dimensions.
VR/EdTech Developers	Prioritize progressive scaffolding, real-time	Medium	CLT analysis suggests scaffolding was key

Stakeholder	Guideline	Priority	Evidence
	feedback, and safe-to-fail design; avoid redundant information channels.		mechanism; redundancy risks noted.
Policy-Makers	Fund pilot VR programs in teacher education; explore low-cost VR alternatives for equity.	Medium	Findings support SDG 4 alignment; digital inequality paragraph highlights access barriers.

5. Limitations and Future Research

This study has several limitations that should be acknowledged. First, the relatively small sample size of 82 prospective teachers may limit the generalizability of the findings. Future research with larger and more diverse populations is needed to confirm and extend these results. Second, the availability and accessibility of VR facilities posed constraints, as limited hardware and infrastructure could affect the scalability and practical implementation of VR interventions in broader educational settings. Third, the intervention duration was relatively short, consisting of only six sessions, which may not fully capture the long-term effects of VR on mathematics anxiety and professional readiness. Longitudinal studies are recommended to evaluate the sustainability of anxiety reduction and the lasting impact on teaching competence.

Additionally, this study was not pre-registered, which is an important consideration for enhancing transparency and reducing potential biases in research. Future studies should consider pre-registration to strengthen methodological rigor. Moreover, further research could explore the development of adaptive VR systems powered by artificial intelligence to tailor learning experiences to individual needs. Cross-cultural replications and investigations into VR's impact across other STEM domains would also provide valuable insights. Addressing these limitations will contribute to a more comprehensive understanding of VR's role in inclusive and quality education.

Several additional limitations warrant acknowledgment. First, the quasi-experimental design with non-equivalent groups limits causal inference; although pretest scores were comparable, unobserved confounders (e.g., prior VR experience, technology attitudes) may have influenced the outcomes. Second, no Simulator Sickness Questionnaire (SSQ) was administered, preventing us from ruling out cybersickness as a potential confound. Although no participant reported discomfort during sessions, the absence of systematic screening is a methodological gap.

Third, the outcome measures used in this study are proximal (self-reported anxiety scales) rather than distal; we did not assess actual mathematical content knowledge gains or real-world teaching performance, which limits conclusions about whether anxiety reduction translates to pedagogical competence. Fourth, the three-week intervention period with no follow-up assessment prevents us from determining whether the anxiety reductions are durable or whether participants experience anxiety relapse once the novelty of VR wears off. Fifth, all participants were drawn from a single private university in Indonesia, which limits generalizability across institutional types, cultural contexts, and national education systems.

6. Conclusion

This quasi-experimental mixed-methods pilot study (N = 82) demonstrates that a six-session VR intervention using MathemaVerse 3D significantly reduced both mathematics academic anxiety (Cohen's $d = 1.45$, $p < .001$) and mathematics pedagogical anxiety ($d = 1.38$, $p < .001$) among prospective elementary school teachers, whereas conventional instruction produced no significant change. Qualitative data confirmed that perceived control, safe-to-fail practice, and embodied engagement were the primary psychological mechanisms driving these reductions. Theoretically, the study advances the field by (a) empirically distinguishing academic from pedagogical mathematics anxiety as separate intervention targets and (b) proposing the Anxiety-Informed TPACK Framework, which integrates affective considerations into technology-enhanced teacher preparation.

So, what do these findings mean in practice? Teacher education programs—particularly those serving populations with elevated mathematics anxiety—should consider integrating anxiety-aware VR modules as a structured complement to traditional microteaching. However, the limitations of this pilot (non-randomized design, single institution, no long-term follow-up, proximal outcomes only) counsel against premature generalization. Multi-site randomized trials with delayed posttests and performance-based outcome measures are essential next steps.

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Conflict of Interest

The authors declare no conflict of interest.

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