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Navigating Critical Thinking Skill Development through Interactive Virtual Reality

Muliawan Firdaus[1*], Mukhtar[2], Muhammad Badzlan Darari[3]
[1]Pendidikan Profesi Guru, Universitas Negeri Medan, Medan, Indonesia
[2,3]Pendidikan Matematika, Universitas Negeri Medan, Medan, Indonesia
Corresponding Author: Muliawan Firdaus muliawanfirdaus@unimed.ac.id

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ABSTRACT

This study investigates the effectiveness of interactive Virtual Reality (VR) in enhancing critical thinking skills among third-year Mathematics Education students in a calculus course. Using a quasi-experimental design, 122 students were divided into experimental and control groups. Over seven weeks, the experimental group used the CalcVR application for interactive problem-solving, while the control group followed traditional methods. Pre- and post-tests showed significant critical thinking improvement in the experimental group ($p < 0.05$), supported by large effect sizes. Qualitative data highlighted the immersive and engaging nature of VR in fostering analytical and inferential skills. The study recommends further exploration of VR in diverse disciplines, extended interventions, and integrating AI for personalized learning. Limitations include the focus on one course and a short intervention period.

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INTRODUCTION

The rapid advancement of technology has revolutionized education, providing innovative tools to address long-standing challenges in teaching complex subjects like mathematics. Among these advancements, VR has emerged as a transformative educational technology, offering immersive, interactive, and engaging learning experiences. VR's potential to bridge the gap between abstract mathematical concepts and students' understanding makes it particularly relevant in calculus, where geometric visualization plays a critical role. Students often struggle to grasp the three-dimensional nature of curves, surfaces, and vector fields, leading to a disconnect between theoretical understanding and practical application (Geewe, 2024). Traditional tools such as textbooks and 2D software, while valuable, are limited in their ability to fully convey spatial relationships. Recent developments in VR technology, have shown promise in addressing these limitations by creating immersive environments where students can explore and manipulate mathematical objects in three dimensions, thereby enhancing engagement, conceptual understanding, and problem-solving skills in STEM education ((Mira et al., 2024); (Pellas et al., 2020)).

Despite its growing integration into educational practices, significant gaps remain in leveraging VR's full potential to improve critical thinking skills, an essential competency in the 21st century. Traditional instructional methods often prioritize procedural knowledge over conceptual understanding, limiting students' ability to apply learning in novel contexts (Saks et al., 2021). While VR applications have demonstrated success in fostering engagement and visualization (Korkut & Surer, 2023), empirical evidence on their effectiveness in enhancing critical thinking remains limited. Furthermore, questions about the accessibility and scalability of VR in diverse educational settings, particularly in resource-constrained environments, need further exploration. Understanding the role of demographic factors such as gender, socio-economic background, and technological familiarity in moderating the impact of VR-based interventions is also crucial to ensure equitable and effective implementation ((Siette et al., 2024); (Tassinari et al., 2022)).

This study aims to evaluate the impact of a VR-based learning intervention on the development of critical thinking skills in a calculus course. By integrating VR technology into the instructional process, the research seeks to address the challenges of geometric visualization while providing empirical evidence on its efficacy in fostering critical thinking. Through a mixed-methods approach, the study investigates the extent to which VR-based learning improves critical thinking compared to traditional instructional methods, explores how demographic factors influence the intervention's effectiveness, examines students' perceptions of VR-based learning, and assesses how technological familiarity moderates its impact. By addressing these questions, this research contributes to the growing body of literature on educational technology, particularly in mathematics education, offering actionable insights for educators seeking to integrate VR into their teaching practices effectively.

THEORETICAL REVIEW

The incorporation of VR in education has gained significant attention in recent years, transforming traditional learning environments into immersive and interactive experiences. Current studies highlight VR's potential to enhance both the cognitive and affective domains of learning. In the cognitive domain, VR has been found to improve students' understanding of complex concepts by providing interactive and spatially immersive environments that facilitate active exploration. For example, studies in STEM education demonstrate that VR enables students to visualize and manipulate abstract scientific and mathematical concepts, leading to deeper conceptual understanding and improved problem-solving skills ((Elme et al., 2022); (Wu et al., 2021); (Zhang et al., 2024)). In the affective domain, VR has been shown to increase student engagement and motivation. The immersive nature of VR fosters a sense of presence, making learning more enjoyable and personally meaningful ((Baxter & Hainey, 2024); (Makransky & Petersen, 2021)). Applications such as virtual laboratories and simulations have proven effective in enhancing students' confidence and curiosity, essential factors for lifelong learning.

Critical thinking is widely recognized as a fundamental competency for academic success and professional readiness. Theories of critical thinking emphasize skills such as analysis, evaluation, and inference, which are crucial for problem-solving and decision-making ((Plummer et al., 2022); (Sharma et al., 2023)). Traditional methodologies for fostering critical thinking include inquiry-based learning, problem-based learning, and case studies. These approaches rely on engaging students in active, reflective, and collaborative learning processes that encourage the questioning of assumptions and the synthesis of knowledge. Interactive tools, particularly those that leverage technology, have been identified as effective in fostering critical thinking. Digital tools such as simulations, interactive software, and gamified learning platforms provide students with real-time feedback, encouraging iterative learning and deeper engagement with the material (Shenoy & Kumar, 2024). However, while these tools are beneficial, they often lack the spatial and experiential depth that VR can provide, limiting their ability to fully engage students in critical thinking activities.

Despite the growing integration of VR in education and its demonstrated benefits, there are notable gaps in the literature regarding its impact on critical thinking. Most existing studies focus on either quantitative outcomes, such as test scores and performance metrics, or qualitative insights, such as student perceptions and experiences. Few studies combine these approaches to provide a comprehensive understanding of VR's effectiveness. Additionally, while research has explored VR's role in enhancing engagement and visualization, there is limited empirical evidence on its ability to develop higher-order cognitive skills like critical thinking (Škola et al., 2020). Furthermore, the moderating effects of demographic factors, such as gender, socio-economic background, and technological familiarity, on VR's efficacy remain underexplored (Moravec et al., 2024). These gaps underscore the need for studies that integrate quantitative and qualitative methodologies to evaluate

VR's impact on critical thinking comprehensively. Such research would provide nuanced insights into how VR can be optimized to meet diverse learner needs and contribute to equitable and effective educational practices.

In summary, while VR has demonstrated promise in enhancing cognitive and affective learning outcomes, its potential to foster critical thinking remains an underexplored area of study. By addressing these gaps, future research can advance our understanding of VR's role as a transformative pedagogical tool, offering actionable insights for its implementation in diverse educational contexts. This study aims to bridge these gaps by evaluating the impact of CalcVR on critical thinking skill development in calculus, combining quantitative analysis of learning outcomes with qualitative insights into student experiences. Such an approach will contribute to the growing body of literature on VR in education and its role in fostering critical, analytical, and inferential thinking skills.

METHODOLOGY

Research Design

This study employs a quasi-experimental design with pre-test and post-test assessments to evaluate the impact of interactive VR interventions on critical thinking skills. The quasi-experimental design was chosen due to practical constraints that prevent full randomization, while still enabling rigorous comparisons between the experimental group and the control group. To minimize bias, participants were randomly assigned to groups, and efforts were made to control external variables such as prior academic performance and technology familiarity. Additionally, group isolation was maintained during the intervention to reduce potential contamination. This design allows the evaluation of VR's educational efficacy while maintaining ecological validity in a real-world context.

Participants

The participants of this study were 122 third-year students from a mathematics education program enrolled in a calculus course at Universitas Negeri Medan (UNIMED). Cluster random sampling was used to select two classes, and participants were further randomly assigned to either the experimental group (n = 60) or the control group (n = 62). The demographic profile included a mean age of 20.5 years, balanced gender representation (55% female, 45% male), and diverse socio-economic backgrounds. Ethical considerations were prioritized by obtaining informed consent from all participants and securing approval from UNIMED ethics committee. This approach ensures that the sample is representative and adheres to ethical standards in educational research.

Materials and Tools

The experimental group utilized CalcVR (https://calcvr.org/), a VR application designed to support the geometric understanding of calculus concepts. CalcVR is compatible with smartphones and Oculus Quest 2 headsets, minimizing hardware costs and increasing accessibility. The app includes interactive lessons, customizable figures, and supplemental materials aligned with the calculus curriculum. The study employed Oculus Quest 2 headsets to provide an immersive experience and Bluetooth controllers for enhanced interactivity. Instructional materials for the experimental group were validated by subject matter experts, while the control group used standard textbooks and multimedia presentations to ensure consistent content delivery. Critical thinking assessments, adapted from Reynders et al. (2020), demonstrating high reliability (Cronbach's α = 0.89), were used to measure learning outcomes.

Procedure

The study was conducted over seven weeks. In the first week, all participants completed a pre-test to establish baseline critical thinking skills. Over the subsequent six weeks, the experimental group participated in two-hour weekly VR sessions using CalcVR, focusing on the visualization and geometric interpretation of calculus concepts. These sessions emphasized analytical, evaluative, and inferential thinking skills through interactive problem-solving scenarios adapted from Heard et al. (2020). The control group received equivalent instructional time using traditional teaching methods. The intervention concluded in the seventh week with a post-test to measure skill development. Additionally, structured interviews with 30 participants from the experimental group provided qualitative insights into their experiences, highlighting the pedagogical and affective impacts of CalcVR. A brief orientation was conducted for both groups to familiarize participants with the tools and procedures.

Data Analysis

Data were analyzed using a mixed-methods approach. Quantitative data from pre-test and post-test assessments were analyzed using Analysis of Covariance (ANCOVA) to control for baseline differences and potential covariates, such as prior academic performance and familiarity with VR technology. Paired t-tests assessed within-group changes, with Cohen's d effect sizes interpreted to determine the magnitude of observed differences (small = 0.2, medium = 0.5, large = 0.8) (Metsämuuronen, 2024). Qualitative data from interviews were transcribed and analyzed using TAMS Analyzer (https://tamsys.sourceforge.io/), to identify emergent themes, such as engagement and skill improvement. Data triangulation integrated qualitative and quantitative findings to enhance the validity and reliability of conclusions (Lemon & Hayes, 2020). This comprehensive approach ensured a nuanced understanding of the intervention's impact.

RESULTS

Quantitative Results

The experimental and control groups are well-balanced in terms of baseline characteristics (Tabel 1), ensuring the validity of subsequent comparisons. The mean age in the experimental group (20.7 ± 1.1 years) and the control group (20.3 ± 1.2 years) was compared using an independent samples *t*-

test, which showed no significant difference between the groups (t_{120} = 1.69, p = 0.09). Similarly, prior academic performance, measured by GPA, was consistent between the experimental group (3.45 ± 0.15) and the control group (3.40 ± 0.18), with the independent samples *t*-test confirming no significant difference (t_{120} = 1.72, p = 0.08).

Table 1. Demographic Data of Participants

Variable	Experimental Group (n = 60)	Control Group (n = 62)
Age (Mean ± SD)	20.7 ± 1.1	20.3 ± 1.2
Gender (Male/Female)	28/32	27/35
Socio-Economic Background (Low/Medium/High)	14/30/16	18/29/15
Familiarity with Technology (Low/Medium/High)	10/24/26	12/28/22
Prior Academic Performance (GPA, Mean ± SD)	3.45 ± 0.15	3.40 ± 0.18

On the other hand, gender distribution, analyzed using a chi-square test, indicated no significant difference between the groups (experimental: 28 males and 32 females; control: 27 males and 35 females; χ_1^2 = 0.03, p = 0.87). Socio-economic background was evenly distributed, with participants categorized as low, medium, and high socio-economic levels (experimental: 14, 30, and 16; control: 18, 29, and 15). A Chi-square test confirmed no significant difference (χ_2^2 = 0.61, p = 0.74). Familiarity with technology was also balanced across the groups (experimental: 10, 24, and 26 in low, medium, and high categories; control: 12, 28, and 22). A chi-square test again showed no significant difference (χ_2^2 = 0.81, p = 0.67). These statistical results confirm that the random assignment process effectively minimized biases, ensuring balanced baseline characteristics across the experimental and control groups. Such balance reinforces the validity of subsequent comparisons and supports the reliability of the study design.

Table 2. Descriptive Statistics for Pre-Test and Post-Test Scores

Variable	Experimental Group (n = 60)	Control Group (n = 62)
Pre-Test (Mean ± SD)	65.2 ± 8.4 (Range: 50-80)	64.8 ± 9.1 (Range: 48-82)
Post-Test (Mean ± SD)	78.5 ± 7.2 (Range: 65-90)	70.3 ± 8.7 (Range: 55-85)

The descriptive statistics (Table 2) reveal comparable baseline critical thinking abilities between the experimental group (65.2 ± 8.4, range: 50–80) and the control group (64.8 ± 9.1, range: 48–82) based on pre-test scores. However, post-test results show a notable improvement in the experimental group, which achieved a mean score of 78.5 ± 7.2 (range: 65–90), compared to the control group's mean of 70.3 ± 8.7 (range: 55–85). The smaller standard deviation in the experimental group's post-test scores indicates more consistent performance among participants (Figure 1). These findings suggest that the interactive VR intervention effectively enhanced critical thinking skills, underscoring its potential as an innovative pedagogical tool.

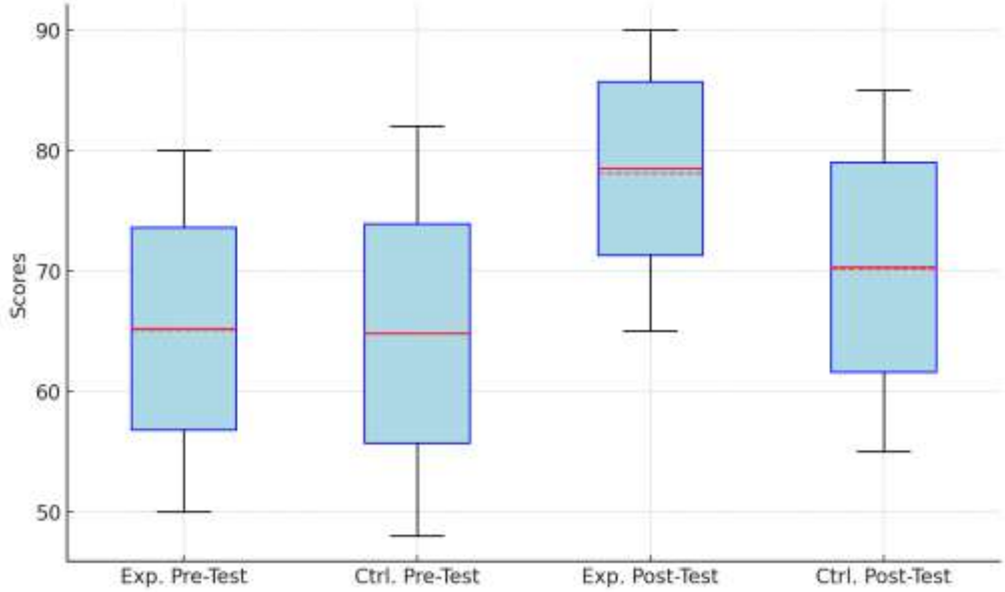

Figure 1. Comparison of Pre-Test and Post-Test Scores Between Groups

The ANCOVA results (Table 3) demonstrate that the inclusion of pre-test scores as a covariate had a statistically significant effect on post-test performance, underscoring the importance of accounting for baseline differences in academic performance. The pre-test scores showed a modest but meaningful influence on the results, with an F value of 4.32 ($p = 0.04$) and a partial eta squared of 0.03, indicating that approximately 3% of the variance in post-test scores can be attributed to this variable. Despite this influence, the adjusted group means highlight a substantial difference between the experimental group (78.3) and the control group (70.2), with the group effect yielding a significant F value of 25.67 ($p < 0.001$) and a partial eta squared of 0.18, accounting for 18% of the variance. These findings confirm that the observed improvement in critical thinking skills was primarily driven by the intervention, while controlling for prior academic performance ensures the robustness of the results. This indicates that the interactive VR intervention was effective in enhancing critical thinking, independent of baseline academic differences.

Table 3. ANCOVA Results

Source	Adjusted Mean (Experimental)	Adjusted Mean (Control)	*F*	*p*-value	Partial Eta Squared
Group	78.3	70.2	25.67	<0.001	0.18
Pre-Test	-	-	4.32	0.04	0.03
Error	-	-	-	-	-

The results of the paired-sample *t*-tests indicate statistically significant improvements in critical thinking scores within both the experimental and control groups (Table 4). For the experimental group, the mean score increased from 65.2 (SD = 8.4) in the pre-test to 78.5 (SD = 7.2) in the post-test, with a highly significant *t*-value of 15.32 ($p < 0.001$) and a large effect size (Cohen's d = 1.52). This substantial improvement reflects the effectiveness of the interactive VR intervention in enhancing critical thinking skills.

Table 4. *t*-Test Results

Group	Pre-Test Mean (SD)	Post-Test Mean (SD)	*t*-Value	*p*-Value	Cohen's *d*
Experimental	65.2 (8.4)	78.5 (7.2)	15.32	<0.001	1.52
Control	64.8 (9.1)	70.3 (8.7)	10.45	<0.001	0.93

Similarly, the control group showed a statistically significant increase in scores, with the mean rising from 64.8 (SD = 9.1) in the pre-test to 70.3 (SD = 8.7) in the post-test ($t = 10.45$, $p < 0.001$, Cohen's $d = 0.93$). Although the control group demonstrated a notable effect size, it was smaller compared to the experimental group, highlighting the greater impact of the CalcVR-based instructional approach. These findings underscore the significant improvements in critical thinking skills in both groups while emphasizing the enhanced effectiveness of the VR intervention in driving larger gains. The larger effect size in the experimental group (1.52 vs. 0.93) further supports the value of innovative pedagogical tools like interactive VR in fostering critical thinking development.

The analysis based on gender indicates significant improvements in critical thinking scores for both males and females across the experimental and control groups (Table 5). In the experimental group, males showed a statistically significant increase from pre-test to post-test ($t = 12.45$, $p < 0.001$, Cohen's $d = 1.40$), while females demonstrated a similarly significant improvement ($t = 13.12$, $p < 0.001$, Cohen's $d = 1.48$). In the control group, both males ($t = 8.75$, $p < 0.001$, Cohen's $d = 0.85$) and females ($t = 9.02$, $p < 0.001$, Cohen's $d = 0.87$) also exhibited significant gains, though the effect sizes were notably smaller compared to the experimental group.

Table 5. Gender Analysis Results

Group	Pre-Test Mean (SD)	Post-Test Mean (SD)	*t*-Value	*p*-Value	Cohen's *d*
Experimental (Male)	66.0 (8.1)	79.0 (6.9)	12.45	<0.001	1.40
Experimental (Female)	64.5 (8.6)	78.1 (7.4)	13.12	<0.001	1.48
Control (Male)	65.0 (9.0)	71.2 (8.5)	8.75	<0.001	0.85
Control (Female)	64.5 (9.2)	69.5 (8.8)	9.02	<0.001	0.87

These findings highlight the effectiveness of the VR intervention in enhancing critical thinking skills for both genders, with females in the experimental group demonstrating slightly more consistent performance (as indicated by smaller standard deviations in post-test scores). The larger effect sizes observed in the experimental group (Cohen's d = 1.40 for males and 1.48 for females) compared to the control group (Cohen's d = 0.85 for males and 0.87 for females) underscore the superior impact of the CalcVR-based approach over traditional instructional methods, regardless of gender.

The analysis based on levels of technology familiarity reveals significant improvements in critical thinking scores across all levels in both the experimental and control groups (Table 6). In the experimental group, participants with low familiarity with technology showed a significant increase from pre-test to post-test (t = 11.32, p < 0.001, Cohen's d = 1.25), while those with medium familiarity demonstrated an even larger effect (t = 14.12, p < 0.001, Cohen's d = 1.50). Participants with high familiarity exhibited the most substantial gains (t = 15.45, p < 0.001, Cohen's d = 1.60). In contrast, the control group showed lower, yet still significant, improvements: low familiarity (t = 6.98, p < 0.001, Cohen's d = 0.78), medium familiarity (t = 8.25, p < 0.001, Cohen's d = 0.85), and high familiarity (t = 9.12, p < 0.001, Cohen's d = 0.92).

Table 6. Technology Familiarity Analysis Results

Group	Pre-Test Mean (SD)	Post-Test Mean (SD)	*t*-Value	*p*-Value	Cohen's *d*
Experimental (Low)	60.5 (7.8)	75.0 (6.5)	11.32	<0.001	1.25
Experimental (Medium)	65.0 (8.2)	78.0 (7.0)	14.12	<0.001	1.50
Experimental (High)	68.0 (8.8)	81.0 (7.3)	15.45	<0.001	1.60
Control (Low)	61.0 (8.0)	67.5 (7.8)	6.98	<0.001	0.78
Control (Medium)	64.2 (8.5)	70.0 (8.4)	8.25	<0.001	0.85
Control (High)	68.5 (9.0)	72.0 (8.5)	9.12	<0.001	0.92

These findings indicate that the VR intervention is effective for participants across all levels of technology familiarity, with particularly pronounced effects for those with higher levels of familiarity. The substantial gains observed in the experimental group suggest that the CalcVR-based instructional approach is accessible and beneficial to participants with varying levels of technological experience. Additionally, the higher effect sizes in participants with greater familiarity highlight how prior technological competence can enhance the effectiveness of VR as a pedagogical tool, further supporting its integration into educational contexts.

Qualitative Results

The qualitative analysis revealed three key themes from interviews with participants in the experimental group: enhanced engagement, immersive learning experiences, and technical or user challenges. Participants overwhelmingly reported increased engagement during VR sessions, describing the learning process as interactive and enjoyable, which motivated them to participate actively. Many emphasized the distinctiveness of VR compared to traditional methods, with one participant stating, "*The VR sessions made learning fun and engaging. I didn't feel like I was just studying; I was part of the problem-solving process*."

Another prominent theme was the immersive nature of CalcVR-based learning, which allowed participants to perceive mathematical concepts as more tangible and relevant to real-world applications. This immersion was consistently linked to improved comprehension. For instance, one participant remarked, "*Using VR made me feel like I was solving real-world problems, which improved my understanding of the topic*." Another highlighted the value of 3D visualization, noting, "*The 3D visualization helped me see the concepts from a different perspective—it felt like I was actually interacting with the material, not just reading about it*."

Despite these benefits, participants also identified initial technical challenges, such as difficulty in navigating the VR interface or discomfort from prolonged use of the headset. However, these issues diminished over time as participants adapted to the technology. One participant shared, "*At first, I struggled with using the VR headset, but after the first session, it became easier to navigate*." Another acknowledged, "*The only downside was wearing the headset for long periods—it was a bit uncomfortable, but the experience was worth it*."

Overall, the findings highlight the effectiveness of VR in fostering engagement and providing an immersive learning environment, while technical challenges were minor and temporary. These insights underline the potential of VR as a transformative tool in mathematics education, offering a balance between innovation and accessibility.

Table 7. Integrative Analysis in CalcVR-Based Learning

Theme	Qualitative Insights	Quantitative Findings	Interpretation
Enhanced Engagement	Participants reported increased motivation and active participation in VR sessions.	Experimental group post-test mean = 78.5 (SD = 7.2); Control group post-test mean = 70.3 (SD = 8.7); Cohen's *d* = 1.52 (males), 1.48 (females).	Increased engagement aligns with significant post-test gains and large effect sizes in the experimental group compared to the control group.

Theme	Qualitative Insights	Quantitative Findings	Interpretation
Immersive Learning	Participants described VR as providing tangible, real-world perspectives that improved comprehension.	Participants with high technological familiarity showed the largest gains: t = 15.45, p < 0.001, Cohen's d = 1.60.	The immersive nature of VR aligns with higher critical thinking scores, particularly among participants familiar with technology.
Technical/User Challenges	Initial challenges with navigation and comfort were noted but diminished over time.	Participants with low technological familiarity also showed significant improvements: t = 11.32, p < 0.001, Cohen's d = 1.25.	Despite initial challenges, participants adapted to VR, and even those with low technological familiarity showed significant learning gains.

The relationship between the qualitative themes and quantitative data provides a comprehensive understanding of the effectiveness of CalcVR-based learning (Table 7). The enhanced engagement reported by participants aligns with the significant improvements in post-test scores observed in the experimental group (mean = 78.5, SD = 7.2), which were notably higher than those in the control group (mean = 70.3, SD = 8.7). The large effect sizes (Cohen's d = 1.52 for males and 1.48 for females) further corroborate the participants' qualitative accounts of increased motivation and active participation during VR sessions.

The immersive learning experiences described by participants also resonate with the quantitative findings. The experimental group, particularly participants with high levels of technological familiarity, achieved the greatest gains in critical thinking skills (t = 15.45, p < 0.001, Cohen's d = 1.60), emphasizing the value of VR's interactive and tangible approach to mathematical concepts. These quantitative results mirror participants' perceptions of how 3D visualization and real-world problem-solving scenarios enhanced their comprehension and engagement. While technical challenges were initially noted, the diminishing impact over time is reflected in the consistent performance improvements across all subgroups within the experimental group. Participants with low technological familiarity, for instance, demonstrated significant learning gains (t = 11.32, p < 0.001, Cohen's d = 1.25), suggesting that VR's accessibility mitigates early user challenges.

This synthesis of qualitative and quantitative findings underscores the multifaceted benefits of CalcVR-based learning. The qualitative insights provide context and depth to the statistical results, illustrating how VR fosters critical thinking through engagement, immersion, and adaptability to diverse user needs, even when minor challenges are present. These complementary perspectives highlight the transformative potential of VR as an innovative pedagogical tool in mathematics education.

DISCUSSION

This study aimed to evaluate the impact of CalcVR, a VR-based instructional tool, on the development of critical thinking skills in a calculus course. By integrating quantitative and qualitative analyses, the findings highlight the transformative potential of VR in addressing the challenges associated with teaching and learning complex mathematical concepts. The discussion below synthesizes these findings, situates them within the broader educational technology literature, and identifies implications for practice, limitations, and directions for future research.

The Role of CalcVR in Enhancing Critical Thinking

The results demonstrate that CalcVR significantly enhanced critical thinking skills compared to traditional instructional methods. The experimental group exhibited a notable increase in post-test scores (mean = 78.5, SD = 7.2) with large effect sizes (Cohen's d = 1.52 for males, 1.48 for females) compared to the control group (mean = 70.3, SD = 8.7, Cohen's d = 0.93). These findings align with prior research emphasizing VR's ability to bridge the gap between abstract mathematical concepts and geometric visualization ((Çakıroğlu et al., 2024); (Skrodzki, 2021)). The interactive and immersive features of CalcVR enabled students to explore three-dimensional objects and spatial relationships, fostering analytical and inferential thinking essential for critical thinking development ((Chelloug et al., 2023); (Gittinger & Wiesche, 2024)). This enhancement in critical thinking skills is particularly noteworthy in a discipline like calculus, where geometric understanding plays a pivotal role in problem-solving. CalcVR's design capitalizes on VR's capacity to create dynamic, manipulable representations of three-dimensional objects, which traditional tools fail to replicate. By allowing students to experiment with mathematical objects and directly observe the effects of their manipulations, CalcVR promotes iterative learning—a key characteristic of critical thinking.

Engagement and Immersion as Catalysts for Learning

The qualitative findings highlight engagement and immersion as pivotal factors in enhancing learning outcomes. Participants consistently reported that VR sessions were more engaging and enjoyable than traditional methods, fostering active participation. This aligns with studies emphasizing that the immersive nature of VR fosters a sense of presence, which enhances motivation and facilitates deeper learning ((Makransky & Mayer, 2022); (Parong & Mayer, 2021)). CalcVR's ability to make abstract calculus concepts tangible further contributed to students' comprehension. The visualization of concepts such as gradients, vector fields, and surface integrals in a three-dimensional space reduced cognitive load by presenting information in a format congruent with human spatial reasoning. This immersive learning environment not only captured students' attention but also encouraged them to critically analyze and synthesize mathematical relationships, supporting findings from prior research on immersive learning technologies (Marougkas et al., 2023). Moreover, the interactive nature of CalcVR, which allowed students to input their own mathematical expressions and receive real-time feedback, created a sense of agency and autonomy. These factors are critical for intrinsic motivation, which has been shown to directly impact critical thinking development (Sari et al., 2021). The alignment of engagement with improved post-test scores demonstrates the pedagogical value of combining immersive technology with student-centered learning approaches.

Addressing Technological and Demographic Factors

This study provides valuable insights into how technological familiarity and demographic factors influence the effectiveness of VR-based learning. Participants with high technological familiarity achieved the most substantial gains (Cohen's d = 1.60), suggesting that prior experience with technology enhances students' ability to navigate and benefit from VR environments. However, the significant improvements observed among participants with low technological familiarity (Cohen's d = 1.25) underscore CalcVR's accessibility and usability across a diverse range of learners.

The findings also demonstrate that CalcVR's impact is equitable across genders, with both male and female participants in the experimental group showing comparable gains. This challenges persistent concerns about potential gender biases in technology adoption and usage, aligning with recent research advocating for inclusive educational technologies (Yassien et al., 2021). The absence of significant gender-based performance differences highlights CalcVR's potential to provide equitable learning opportunities, a critical consideration in promoting diversity and inclusion in STEM education.

Implications for Educational Practice

The results have significant implications for the integration of VR into mathematics education. First, the effectiveness of CalcVR in fostering critical thinking suggests that VR-based tools can complement traditional teaching methods by addressing key conceptual and engagement challenges. For educators, this means that adopting VR tools like CalcVR can enrich instructional practices by providing students with novel ways to interact with mathematical content (AlGerafi et al., 2023). Second, CalcVR's compatibility with cost-effective hardware and its minimal technological requirements highlight its scalability for resource-constrained environments (Georgiou & Ioannou, 2021). This is particularly relevant for educational institutions in developing regions, where access to advanced technology is often limited. By demonstrating the feasibility of implementing VR-based learning with minimal investment, this study contributes to discussions on the democratization of educational technology. Finally, the findings emphasize the importance of designing VR interventions that align with pedagogical goals. CalcVR's focus on critical thinking through visualization and interaction demonstrates the need for VR tools that are not only technologically sophisticated but also pedagogically grounded (Yıldırım et al., 2020). Educators should prioritize VR applications that align with curricular objectives and foster higher-order cognitive skills.

Limitations and Directions for Future Research

Despite its contributions, this study has limitations that must be acknowledged. The quasi-experimental design, while practical, limits the ability to establish causal relationships. Future research employing randomized controlled trials could provide more definitive evidence of VR's impact on critical thinking skills. Additionally, the short duration of this study restricts insights into the long-term effects of CalcVR on academic performance and critical thinking development. Longitudinal studies are needed to assess the sustained impact of VR-based learning. Another limitation is the exclusive focus on calculus. While this provides valuable insights into STEM education, future research should explore VR's applicability to other subjects and disciplines. For instance, extending VR applications to social sciences or humanities could uncover new dimensions of its pedagogical value. Furthermore, this study primarily relied on self-reported qualitative data to assess engagement and immersion. Incorporating additional measures, such as physiological responses or eye-tracking, could provide more objective insights into students' cognitive and emotional experiences during VR sessions. Additionally, exploring the integration of VR with emerging technologies, such as artificial intelligence or adaptive learning systems, could enhance its capacity for personalized and dynamic instruction (Gligorea et al., 2023).

CONCLUSIONS AND RECOMMENDATIONS

This study provides compelling evidence of the potential for CalcVR, a VR-based instructional tool, to enhance critical thinking skills in calculus. By bridging the gap between abstract mathematical concepts and practical understanding, CalcVR addresses persistent challenges in STEM education, particularly in visualizing and interacting with complex three-dimensional objects. Through an integration of quantitative and qualitative analyses, this research highlights the transformative capabilities of immersive learning environments to foster critical thinking, engagement, and comprehension. The findings demonstrate that CalcVR significantly outperforms traditional instructional methods in improving critical thinking skills, with participants in the experimental group showing substantial gains in post-test scores across gender and levels of technological familiarity. These results underscore the pedagogical value of combining VR technology with student-centered approaches that emphasize interactive exploration, immediate feedback, and real-world problem-solving. The qualitative insights further affirm the role of engagement and immersion as catalysts for learning, with participants reporting increased motivation, enjoyment, and deeper understanding during VR sessions. Moreover, the accessibility and scalability of CalcVR highlight its potential as a practical solution for diverse educational contexts, including resource-constrained environments. By leveraging cost-effective hardware and emphasizing usability across a range of technological proficiencies, CalcVR demonstrates that innovative educational technologies can be inclusive and adaptable. Despite these promising outcomes, this study acknowledges certain limitations, such as the quasi-experimental design and short intervention duration. Future research should expand the scope of VR applications to other disciplines, employ longitudinal designs to assess sustained impacts, and explore integrations with emerging technologies like artificial intelligence and adaptive learning systems. Additional measures, such as physiological or behavioral analytics, could provide richer insights into the cognitive and emotional dimensions of VR-based learning. In summary, this study establishes CalcVR as a transformative tool for fostering critical thinking in calculus and sets a foundation for further exploration of VR's broader applications in education. By aligning technological innovation with pedagogical goals, educators and policymakers can harness the potential of VR to create equitable, engaging, and effective learning environments, ultimately preparing students with the critical skills necessary for academic and professional success in the 21st century.

FURTHER STUDY

Future studies should expand on this research by exploring the application of VR-based tools like CalcVR in other disciplines and educational contexts. Longitudinal studies are recommended to evaluate the sustained impact of VR on critical thinking and learning outcomes over time. Integrating VR with emerging technologies such as artificial intelligence and adaptive learning systems could further personalize and enhance the learning experience. Additionally, incorporating physiological or behavioral analytics may provide deeper insights into the cognitive and emotional aspects of VR-based education. These directions aim to maximize the potential of immersive learning environments in fostering critical skills and improving educational equity.

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