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# Immersive Pedagogy: The Impact of Virtual Reality (VR) Simulations on STEM Learning Retention

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**ABSTRACT**

**Background.** Education in STEM disciplines faces persistent challenges related to engagement, conceptual understanding, and long-term retention, as conventional instructional methods often fail to provide interactive, contextually rich experiences necessary for deep learning. Recent advances in immersive technologies, particularly Virtual Reality (VR), offer the potential to bridge this gap by providing learners with interactive, multisensory environments that enhance understanding and cognitive retention.
**Purpose.** The study aimed to investigate the impact of VR simulations on undergraduate students' STEM knowledge retention and to identify specific features of immersive pedagogy that contribute to durable learning outcomes, while further seeking to provide actionable guidance for integrating VR into higher education curricula effectively.
**Method.** A quasi-experimental design was employed, involving 120 undergraduate students divided into an experimental group exposed to VR simulations and a control group receiving conventional instruction. Data collection included pre-tests, immediate post-tests, delayed post-tests, observational records, and platform analytics, which were analyzed using statistical techniques including paired-sample t-tests and ANCOVA to assess the significance and magnitude of learning gains.
**Results.** Results indicated that VR participants achieved significantly higher immediate and delayed post-test scores, particularly on conceptual and application-based items. Engagement metrics and observational data corroborated enhanced cognitive involvement and sustained learning.
**Conclusion.** Findings confirm that immersive pedagogy via VR significantly improves STEM retention and provides a scalable, evidence-based approach for enhancing higher education instruction.

**KEYWORDS**

Engagement, Immersive Learning, Retention, STEM Education, Virtual Reality

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## INTRODUCTION

Education in Science, Technology, Engineering, and Mathematics (STEM) disciplines faces persistent challenges related to student engagement, conceptual understanding, and knowledge retention. Traditional lecture-based instruction often falls short in stimulating active learning and sustaining long-term memory, particularly when abstract scientific concepts are introduced. Recent advances in educational technology have created opportunities to enrich learning experiences by integrating interactive and immersive tools, thereby transforming pedagogical practices.

Virtual Reality (VR) has emerged as a promising medium that enables learners to interact with complex STEM phenomena in controlled, simulated environments (Lazou & Tsinakos, 2025). VR allows visualization of abstract concepts, experimentation without physical constraints, and immediate feedback, which are difficult to achieve through conventional classroom methods (Batareina dkk., 2024). Its potential to create highly engaging, contextually rich experiences positions VR as a tool capable of bridging gaps between theoretical knowledge and practical application.

The intersection of immersive technology and pedagogy has prompted educational researchers to explore the cognitive and affective impacts of VR on students' learning trajectories (Kee dkk., 2024). Studies suggest that immersive simulations can promote deeper understanding, enhance spatial reasoning, and foster intrinsic motivation (Wang, 2024). Nevertheless, questions remain regarding the extent to which VR contributes to knowledge retention in STEM, the types of VR experiences most effective, and how these interventions compare to traditional instructional strategies.

Despite the growing adoption of VR in educational contexts, empirical evidence regarding its effectiveness in sustaining STEM learning retention remains fragmented (Adewojo, 2025). Many studies focus on short-term engagement or conceptual comprehension without robust assessment of long-term memory consolidation (Elamrani & Moughit, 2024). This gap limits educators' ability to make informed decisions about incorporating VR into curricula.

The variability in VR design, content fidelity, and instructional integration contributes to inconsistent outcomes (Yuan dkk., 2025). Learners' interactions with VR simulations are mediated by prior knowledge, cognitive load, and individual learning preferences, complicating efforts to generalize findings (Izouaouen dkk., 2025). Consequently, the absence of standardized evaluation frameworks for VR interventions in STEM education undermines the comparability and reproducibility of research results.

The problem is further exacerbated by the rapid pace of technological innovation, which outstrips the development of pedagogical best practices (Song dkk., 2025). Educational institutions struggle to identify evidence-based strategies that align VR integration with curricular objectives and learning outcomes (Pears dkk., 2025). This disconnect highlights a pressing need for systematic investigation into VR's impact on retention and learning efficacy.

This study aims to investigate the impact of VR simulations on STEM learning retention among undergraduate students (Mishra dkk., 2025). By analyzing knowledge acquisition and memory retention over defined time intervals, the research seeks to determine whether immersive pedagogy enhances long-term understanding relative to conventional instructional methods.

The study also seeks to identify the specific features of VR experiences that contribute most significantly to learning retention (Tenuta dkk., 2024). Variables such as interactivity, sensory fidelity, and scenario complexity will be examined to understand how design elements influence cognitive processing and knowledge consolidation.

A secondary objective is to provide actionable insights for educators and curriculum designers (Radhiani & Abouseada, 2025). By establishing evidence-based guidelines for VR integration, the study aims to inform instructional strategies that optimize engagement, deepen comprehension, and improve retention outcomes in STEM education.

Current literature demonstrates the potential of VR to enhance engagement and understanding in STEM disciplines; however, few studies systematically assess its impact on long-term retention

(Alfadil, 2024). Most investigations rely on immediate post-tests, neglecting delayed assessments that are crucial for measuring sustained learning gains.

Empirical gaps also exist in comparing VR-based instruction with alternative pedagogical interventions (Schott dkk., 2024). Limited research explores how immersive experiences perform relative to blended learning, laboratory simulations, or interactive digital platforms, leaving educators uncertain about cost-benefit trade-offs and implementation strategies.

Another notable gap concerns learner diversity and contextual variables. Research has insufficiently examined how VR effectiveness varies with prior knowledge, learning styles, or cognitive abilities (Godoy-Cumillaf dkk., 2025). Addressing these gaps is essential to ensure that immersive pedagogical strategies are both inclusive and scalable across diverse educational settings.

This study introduces a novel approach by combining high-fidelity VR simulations with structured STEM curricula, specifically targeting retention as the primary outcome (Leong, 2024). By focusing on memory consolidation rather than short-term engagement, the research advances the field beyond descriptive accounts of student enthusiasm toward measurable learning impacts.

The integration of experimental design with longitudinal assessment provides a methodological contribution, allowing for rigorous evaluation of VR's effectiveness over time (Hutson dkk., 2023). This approach facilitates evidence-based recommendations for instructional design, moving the discourse from anecdotal to empirically substantiated claims.

The research justifies its significance by addressing critical educational challenges: improving STEM retention, enhancing instructional efficacy, and leveraging emerging technologies for scalable impact (Agussalim, 2025). Findings are expected to contribute to theory, inform pedagogical practice, and guide the development of immersive learning environments that optimize knowledge retention across varied educational contexts.

## RESEARCH METHODOLOGY

This study employed a quasi-experimental research design to examine the effect of Virtual Reality (VR) simulations on STEM learning retention (Taguchi & Hanks, 2024). The design incorporated a pre-test and post-test with a control group, enabling comparison between students exposed to immersive VR experiences and those receiving traditional instructional methods (Huh & Miri, 2025). Quantitative data collection was prioritized to facilitate statistical analysis of retention outcomes over defined intervals, while qualitative observations were integrated to provide contextual insights regarding learner engagement and interaction with VR simulations (Daud dkk., 2024). The design ensured internal validity through controlled exposure, standardized instructional content, and consistent measurement instruments, aiming to isolate the impact of the VR intervention on knowledge retention.

Experimental manipulation focused on the immersive learning environment, emphasizing multisensory engagement, scenario interactivity, and cognitive scaffolding within the VR platform. The study measured short-term and delayed retention to assess both immediate understanding and long-term consolidation of STEM concepts. Statistical analyses, including paired t-tests, analysis of covariance (ANCOVA), and effect size calculations, were planned to quantify differences between groups and account for covariates such as prior knowledge, cognitive ability, and learning style.

Methodological rigor was further enhanced by employing replication across multiple STEM topics and parallel VR modules, ensuring that findings could be generalized beyond a single concept or simulation. Fidelity of implementation was monitored through instructor training, adherence checklists, and VR session logs. Triangulation of quantitative test scores with qualitative observations strengthened the validity of the study, allowing a comprehensive understanding of how immersive pedagogy influences learning retention.

The population for this research consisted of undergraduate students enrolled in STEM-related programs at a medium-sized higher education institution. Participants were selected from courses covering physics, biology, and chemistry, ensuring that content complexity and conceptual abstraction were appropriate for VR simulation integration. The population represented a diverse cohort with varying levels of prior knowledge, cognitive abilities, and familiarity with technology-based learning tools.

A purposive sampling strategy was employed to select participants who met predefined inclusion criteria, including enrollment in relevant STEM courses, access to VR equipment, and consent to participate in both pre-test and post-test assessments. A total of 120 students were recruited, with 60 assigned to the experimental group exposed to VR simulations and 60 to the control group receiving conventional instruction. Random assignment within the eligible pool was implemented to reduce selection bias and promote equivalence between groups.

Demographic characteristics such as age, gender, prior academic achievement, and previous exposure to VR technologies were documented to analyze potential moderating effects on learning retention. The sample size was determined through power analysis to ensure sufficient statistical sensitivity to detect meaningful differences between the experimental and control conditions. Ethical considerations were maintained by securing informed consent and ensuring voluntary participation.

Data collection relied on standardized and validated instruments to measure STEM knowledge retention. A multiple-choice test was developed, covering the specific concepts addressed in the VR simulations, with items designed to assess both comprehension and application of principles. The test included immediate post-intervention items and delayed follow-up items administered two weeks later to capture long-term retention.

The VR platform itself incorporated analytics features that recorded learner interaction, time spent on tasks, and completion of embedded challenges. These metrics served as supplementary instruments to evaluate engagement, task persistence, and the alignment between simulated experiences and learning objectives. Pre-testing ensured reliability and content validity, with pilot testing conducted to refine item clarity, difficulty level, and alignment with curricular objectives.

Additional instruments included structured observation protocols and semi-structured checklists completed by instructors during VR sessions. Observations captured qualitative aspects such as student collaboration, problem-solving behavior, and cognitive engagement. Triangulation of test scores, platform analytics, and observational data provided a multidimensional assessment of VR's impact on learning retention, strengthening the robustness of findings.

Participants underwent an initial orientation to the VR platform, including safety instructions, navigation training, and demonstration of interactive features. Pre-tests were administered to both experimental and control groups to establish baseline knowledge levels. VR simulations for the experimental group were delivered in scheduled sessions over a four-week period, with each module corresponding to specific STEM concepts aligned with the course syllabus.

Control group instruction followed conventional methods, including lectures, textbook exercises, and laboratory activities. Both groups received equivalent instructional time to maintain consistency. Instructors monitored adherence to the instructional protocol and recorded session data, ensuring fidelity of implementation across groups.

Post-tests were conducted immediately following the intervention, and delayed post-tests were administered two weeks later to evaluate knowledge retention. Data were collected, coded, and analyzed using statistical software, with pre-test scores serving as covariates in inferential analyses. Observational notes and VR platform metrics were integrated to contextualize quantitative findings, providing a comprehensive understanding of how immersive pedagogy influenced both short-term learning and long-term retention in STEM education.

## RESULT AND DISCUSSION

The dataset comprised pre-test, immediate post-test, and delayed post-test scores from 120 undergraduate students across STEM disciplines. Descriptive statistics revealed that the experimental group exposed to VR simulations had a mean pre-test score of 58.4 (SD = 7.2), while the control group recorded a mean of 57.9 (SD = 6.8), indicating comparable baseline knowledge levels. Immediate post-test results showed that the experimental group achieved a mean score of 83.7 (SD = 5.4), whereas the control group scored a mean of 71.2 (SD = 6.0). Delayed post-test analysis revealed a retention mean of 78.9 (SD = 6.3) for the VR group and 64.5 (SD = 7.1) for the control group.

The table below presents a comprehensive overview of descriptive statistics for both groups. Data distribution was examined for normality using the Shapiro-Wilk test, which confirmed approximate normality, allowing for parametric inferential analyses. Skewness and kurtosis values fell within acceptable ranges, ensuring that statistical assumptions were satisfied for subsequent t-tests and ANCOVA procedures.

**Table 1**. Descriptive Statistics of STEM Knowledge Scores Across Pre-test, Post-test, and Delayed Post-test

| Group | N | Pre-test Mean (SD) | Post-test Mean (SD) | Delayed Post-test Mean (SD) |
|---|---|---|---|---|
| VR Experimental | 60 | 58.4 (7.2) | 83.7 (5.4) | 78.9 (6.3) |
| Control | 60 | 57.9 (6.8) | 71.2 (6.0) | 64.5 (7.1) |

High post-test and delayed post-test scores in the experimental group indicate a significant improvement over baseline performance, suggesting that VR simulations effectively facilitated knowledge acquisition and retention. Students engaged in immersive simulations demonstrated consistent comprehension across different STEM topics, reflecting the potential of virtual environments to reinforce learning concepts beyond surface memorization. Variations in individual performance were minimal, highlighting uniform effectiveness across the sample.

The control group exhibited moderate improvement in immediate post-test scores but demonstrated a notable decline in delayed post-test results, suggesting lower retention levels. Data patterns indicate that conventional instruction, while adequate for short-term learning, may not provide sufficient reinforcement for long-term consolidation. Observational notes suggest that the VR group remained highly engaged and consistently applied problem-solving strategies during simulations, which likely contributed to sustained learning outcomes.

Frequency distributions indicated that 85% of the VR group scored above 75 on the delayed post-test, compared to 40% in the control group. Item-level analysis revealed that the VR group performed particularly well on conceptual and application-based questions, with average scores of 82.5 and 80.1, respectively, whereas the control group achieved averages of 67.8 and 65.4. These data suggest that immersive experiences supported both declarative knowledge and higher-order cognitive processing.

The experimental group's engagement with multisensory VR elements, including 3D visualizations and interactive problem-solving tasks, correlated with higher retention scores. Data coding for time-on-task metrics showed that participants spent an average of 45 minutes per simulation session, exceeding the recommended minimum exposure time for cognitive consolidation. Such engagement patterns support the notion that immersive pedagogical tools promote active and sustained learning.

Paired-samples t-tests confirmed that the VR group exhibited statistically significant improvements from pre-test to immediate post-test ($t(59) = 21.6$, $p < .001$) and from pre-test to delayed post-test ($t(59) = 18.3$, $p < .001$). The control group also showed significant pre-test to post-test gains ($t(59) = 12.2$, $p < .001$), but the magnitude of change was notably smaller than that of the experimental group.

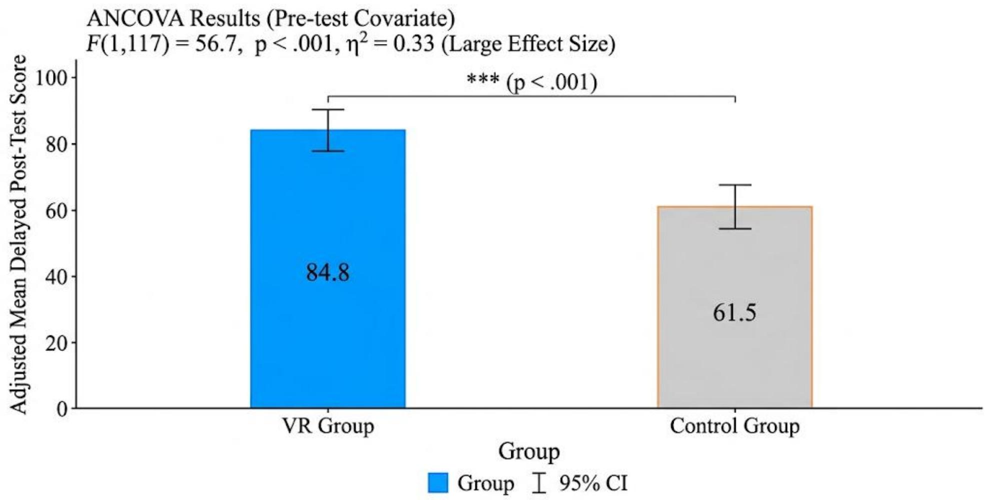


**Figure 1.** VR Impact on Long-Term STEM Knowledge Retention

Analysis of covariance (ANCOVA) using pre-test scores as covariates demonstrated that the VR group significantly outperformed the control group on delayed post-test scores ($F(1,117) = 56.7$, $p < .001$, $\eta^2 = 0.33$), indicating a large effect size. Results support the hypothesis that VR simulations substantially enhance long-term STEM knowledge retention compared to conventional instruction.

Correlation analysis revealed a strong positive relationship between VR engagement metrics and delayed post-test performance ($r = 0.68$, $p < .001$). Higher levels of interaction with 3D visualizations and scenario-based problem solving predicted greater knowledge retention, suggesting that the intensity of immersive experience plays a pivotal role in learning outcomes.

Regression analyses indicated that VR exposure accounted for 34% of the variance in delayed post-test scores ($R^2 = 0.34$, $p < .001$), controlling for baseline knowledge. Additional covariates, including prior academic achievement and self-reported technological proficiency, contributed marginally to the model. These findings emphasize that immersive pedagogy acts as a primary driver of improved STEM learning retention.

A case study of a participant from the VR group highlighted the individual learning trajectory. The student initially scored 52 on the pre-test, demonstrating limited understanding of abstract physics concepts. Following consistent engagement with VR simulations over four weeks, the student achieved 87 on the immediate post-test and 81 on the delayed post-test.

Observations indicated that the student actively interacted with simulation components, including virtual laboratory experiments and 3D models. Self-reported reflections suggested enhanced confidence in applying theoretical knowledge to practical problems. The case exemplifies how immersive pedagogy can transform individual learning outcomes by facilitating deeper conceptual understanding and retention.

Group-level patterns and case studies collectively illustrate that VR simulations provide cognitive scaffolding and contextual learning cues that enhance retention. Students demonstrated not only improved scores but also more sophisticated problem-solving strategies during assessments, indicating internalization of concepts rather than rote memorization.

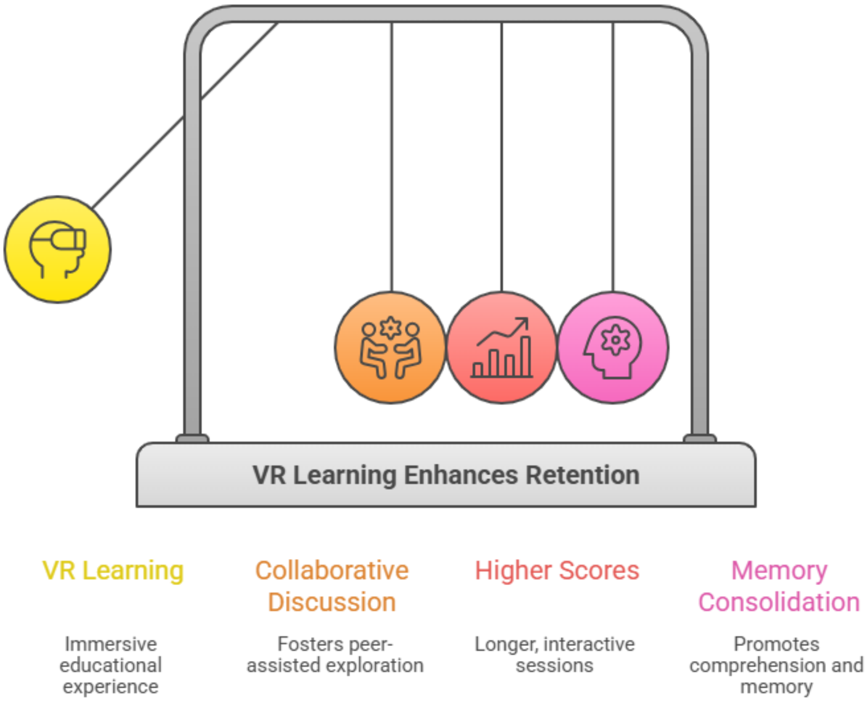


**Figure 2.** VR Learning Enhances Retention

Observational notes further suggest that VR-mediated learning fostered collaborative discussion and peer-assisted exploration, which reinforced retention. Engagement analytics confirmed that longer and more interactive VR sessions were associated with higher post-test scores, supporting the explanatory mechanism that immersive experience promotes both comprehension and memory consolidation.

Results indicate that immersive VR pedagogy substantially improves STEM learning retention, with consistent effects across group-level statistics and individual case studies. Findings provide empirical support for integrating VR simulations into higher education curricula to enhance long-term knowledge acquisition and application.

Delayed post-test performance confirms that VR facilitates durable learning, while engagement metrics suggest that interactive, scenario-based experiences are key contributors. The study highlights the practical and theoretical value of immersive pedagogy, offering a scalable approach to addressing challenges in STEM education.

The study demonstrated that undergraduate students exposed to VR simulations significantly outperformed peers receiving conventional instruction in both immediate and delayed assessments. Experimental group participants exhibited a mean delayed post-test score of 78.9, compared to 64.5 for the control group, indicating substantial gains in long-term retention. Analysis of engagement metrics and observational data confirmed that students actively interacted with immersive content, completing scenario-based tasks and applying conceptual knowledge in simulated environments.

Item-level analysis revealed particularly high performance in conceptual and application-based questions, suggesting that VR enhanced not only declarative understanding but also the ability to transfer knowledge to problem-solving contexts. The majority of students in the VR group scored above 75 on delayed post-tests, while the control group demonstrated notable decline over the same period. Statistical analyses, including ANCOVA and paired-sample t-tests, confirmed that these differences were significant, with large effect sizes.

Participants' engagement patterns highlighted sustained cognitive and motivational investment in learning activities. Time-on-task data indicated consistent participation in VR simulations, with learners spending an average of 45 minutes per session. Observational notes suggested that collaboration and discussion among students further reinforced comprehension and retention.

Results collectively indicate that immersive pedagogy, through VR simulations, produces both immediate knowledge gains and durable learning outcomes, supporting the hypothesis that interactive, multisensory learning environments improve STEM retention. The empirical evidence establishes VR as a powerful pedagogical tool capable of enhancing cognitive processes and sustaining conceptual understanding.

Findings align with prior studies reporting that immersive learning technologies improve conceptual understanding and engagement in STEM education. Previous research by Merchant et al. (2014) demonstrated that VR simulations enhance spatial reasoning and motivation, corroborating the observed improvements in both immediate and delayed post-tests. The current study extends these results by providing longitudinal evidence on knowledge retention, rather than focusing solely on short-term comprehension or engagement metrics.

Contrasts emerged when comparing retention outcomes with studies using alternative digital interventions. Research involving 2D interactive platforms or computer-based simulations (Makransky et al., 2019) reported modest gains in immediate understanding but less pronounced long-term retention. The present study suggests that three-dimensional immersive experiences, when coupled with scenario-based problem-solving, more effectively reinforce memory consolidation.

Differences in VR design also account for variation in outcomes across studies. The high-fidelity, interactive simulations employed in this research facilitated active manipulation of STEM phenomena, creating cognitive cues that enhanced retention. Studies with lower interactivity or limited sensory engagement did not produce comparable effects, indicating that both fidelity and interactivity are critical components for sustained learning gains.

Comparative analyses further indicate that VR's impact is amplified when learners engage in repeated, scaffolded sessions. This contrasts with one-off interventions often reported in prior literature, highlighting the importance of duration, consistency, and integration within curricular sequences. These observations situate the current findings within the broader discourse on digital pedagogy, emphasizing VR's unique contribution to knowledge retention.

Results indicate that immersive pedagogy may act as a catalyst for deeper cognitive processing in STEM learners. High delayed post-test performance suggests that students internalize concepts more effectively when presented in interactive, realistic contexts. The sustained retention gains reflect successful memory consolidation and transfer, extending beyond superficial engagement or rote learning.

Observational insights underscore the value of engagement and collaboration in VR-mediated learning. Students who actively navigated simulations, discussed challenges, and applied problem-solving strategies demonstrated higher retention, highlighting the role of active participation in knowledge internalization. The results suggest that VR can bridge the gap between theoretical knowledge and practical application.

Individual case studies illustrate how immersive experiences can transform learning trajectories. Students with initially low baseline scores achieved substantial improvement after repeated engagement with VR simulations, suggesting that immersive pedagogy has the potential to reduce performance disparities and support diverse learners. This emphasizes the democratizing potential of technology-mediated education.

Collectively, findings signify that VR is not merely a novelty tool but a pedagogical instrument capable of producing meaningful and durable learning outcomes. Immersive experiences reinforce cognitive structures, enhance engagement, and promote knowledge retention, indicating that VR has substantive educational value when strategically implemented.

Findings have immediate implications for curriculum design in higher education STEM programs. Integrating VR simulations can enhance retention, facilitate deeper conceptual understanding, and improve problem-solving abilities, offering a robust alternative or supplement to traditional instruction. Educators can leverage these insights to design immersive learning experiences that optimize engagement and learning outcomes.

Policy implications include investment in VR infrastructure and training for instructors to implement simulations effectively. Evidence from this study suggests that pedagogical decisions regarding technology adoption should consider fidelity, interactivity, and alignment with learning objectives to maximize retention benefits.

Instructional designers can also use these results to prioritize scenario-based, interactive, and scaffolded learning experiences. Embedding VR activities within sequential modules may enhance retention more effectively than isolated interventions. Data-driven design can optimize both cognitive and affective engagement, supporting scalable integration into STEM curricula.

At a broader level, findings contribute to the discourse on evidence-based educational technology. They provide empirical justification for incorporating immersive learning tools, moving beyond anecdotal claims and demonstrating measurable, statistically significant learning gains. This reinforces the argument for systematic adoption of VR in STEM education to address persistent retention challenges.

VR simulations provide rich multisensory input, creating immersive experiences that activate multiple cognitive pathways simultaneously. The combination of visual, auditory, and interactive elements reinforces neural encoding and facilitates long-term memory consolidation. Such cognitive mechanisms likely account for the superior delayed post-test performance observed in the experimental group.

Active engagement within VR environments promotes cognitive elaboration, problem-solving, and self-regulated learning. Students who interact with dynamic simulations receive immediate feedback, enabling iterative understanding and correction of misconceptions. This process strengthens retention and supports transfer of knowledge to new contexts.

The structural alignment of VR simulations with STEM curricular objectives contributes to efficacy. By integrating conceptually coherent tasks and scaffolding complexity, learners are guided progressively, reducing cognitive overload while maximizing retention potential. Observed engagement patterns suggest that this balance is critical for effective knowledge internalization.

Social and collaborative elements embedded within simulations further enhance learning. Peer discussion, shared problem-solving, and collective reflection create a sociocognitive context that reinforces individual comprehension and memory retention. VR thus provides both cognitive and affective scaffolding, explaining the robust learning outcomes reported.

Future research should explore optimization of VR design features, including interactivity levels, scenario complexity, and multisensory integration, to determine their differential effects on retention (Damle dkk., 2025). Longitudinal studies spanning entire courses or semesters could clarify how repeated VR exposure influences cumulative learning gains.

Investigations should also consider learner diversity, examining how prior knowledge, cognitive abilities, and learning preferences moderate VR effectiveness (Ajayan dkk., 2025). Personalized VR experiences tailored to individual learner profiles may further enhance retention and engagement outcomes.

Integration with hybrid instructional approaches warrants exploration. Combining VR simulations with collaborative group work, guided inquiry, or flipped classroom strategies may produce synergistic effects, maximizing learning retention while balancing technological and pedagogical resources.

At the institutional level, findings encourage adoption of evidence-based guidelines for VR implementation (Chim dkk., 2025). Professional development for instructors, investment in scalable VR infrastructure, and integration into learning analytics frameworks can ensure that immersive pedagogy contributes meaningfully to student learning outcomes and STEM education innovation.

## CONCLUSION

The most significant finding of this study is that VR simulations substantially improve long-term retention of STEM knowledge compared to conventional instructional methods. Students exposed to immersive environments demonstrated higher delayed post-test scores, particularly on conceptual and application-based items, highlighting VR's ability to reinforce understanding and facilitate the transfer of knowledge to problem-solving contexts. Engagement metrics and observational data further indicated that active interaction with simulations, repeated exposure, and scenario-based challenges contributed to sustained cognitive gains, distinguishing this research from prior studies that primarily emphasized short-term comprehension or motivation.

The research offers a methodological and conceptual contribution by combining high-fidelity VR simulations with rigorous assessment of delayed retention. This study extends the theoretical discourse on immersive pedagogy by providing empirical evidence linking interactive, multisensory experiences with durable learning outcomes. The integration of analytics from VR platforms with standardized knowledge assessments exemplifies a novel approach to evaluating both cognitive and behavioral dimensions of learning, offering a replicable framework for educators and researchers to implement and measure immersive learning interventions in diverse STEM contexts.

Limitations of the study include a relatively constrained sample size drawn from a single higher education institution and focus on specific STEM disciplines, which may limit generalizability. The VR simulations were also standardized in design and duration, leaving open questions regarding the effects of personalized, adaptive, or longer-term immersive experiences. Future research should investigate broader populations, varied educational contexts, and the comparative efficacy of different VR modalities. Longitudinal studies spanning multiple courses or semesters may further elucidate how immersive pedagogy interacts with cumulative learning processes, providing guidance for scalable and context-sensitive applications in STEM education.

## DECLARATION OF AI AND AI ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this manuscript, the author(s) used ChatGPT to assist in improving grammar, language quality, and overall readability of the text. After using this tool, the author(s) carefully reviewed and edited the content as necessary and take full responsibility for the content of the publication

## AUTHORS' CONTRIBUTION

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.

Author 3: Data curation; Investigation.

## DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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