Enhancing Educational Outcomes Through Hybrid Simulation Methods

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Purpose To investigate long-term effectiveness of immersive virtual reality (VR) compared with traditional learning methods in a radiography education program through a comparative longitudinal analysis.

Methods For 3 years, educational outcomes, such as student engagement and knowledge retention, were assessed to determine the effects of hybrid simulation methods incorporating immersive VR. The study used Virtual Medical Coaching's X-Ray Pro VR software to integrate VR into the curriculum.

Results The data and graphical analyses substantiate the effectiveness of the hybrid learning model over traditional physical methods in terms of academic and practical performance metrics, affective measures, and career preparedness. Students using a hybrid of VR and physical simulations had significantly higher mean posttest scores, mean practical exam scores, career readiness, internship performance, mean motivation level, and mean engagement level compared with the students who only used physical simulation machines ($P < .001$).

Discussion The significant improvements in student engagement and retention observed in this study suggest that VR can effectively address some of the limitations of traditional learning methods. The immersive nature of VR might provide a more engaging and interactive learning environment, leading to better educational outcomes. These findings support the potential for VR to be a valuable tool in higher education, particularly in fields that benefit from simulation-based training. However, further research is needed to explore the practical challenges of implementing VR at scale and to evaluate its effectiveness across various educational disciplines.

Conclusion This study uniquely contributes to the literature by providing empirical evidence of the sustained benefits of VR in educational settings, highlighting its potential to transform learning experiences and outcomes. The implications of these results suggest the need for educational institutions to consider integrating VR technologies strategically into their curricula to optimize teaching and learning effectiveness.

Keywords | *virtual reality, education, real-world scenarios, physical simulation*

Virtual reality (VR) has emerged as a powerful tool in higher education, offering immersive experiences that can significantly enhance learning outcomes.[1] Traditional physical simulations have been used in disciplines such as engineering, health care, and natural sciences to provide hands-on experience. However, these methods have inherent limitations, such as high costs and logistical challenges. Previous studies, including those by O'Connor and Rainford,[2] Dede,[3] and Rowe et al[4] have demonstrated that VR can provide engaging and authentic learning experiences that surpass the capabilities of conventional methods. Despite these promising findings, there is a notable lack of longitudinal studies examining the long-term effects of VR on student engagement, knowledge retention, and skill acquisition. This study aims to address this gap by conducting a comparative longitudinal analysis of VR and traditional physical simulations during a 3-year period.

Learning theories such as experiential learning[5] and cognitive load theory[6] suggest that optimal learning environments mimic real-world scenarios while minimizing unnecessary cognitive load. Experiential learning theory emphasizes learning through experience and reflection, making it highly relevant to this study. VR provides immersive, hands-on experiences that enhance learning by simulating real-world scenarios, aligning with Kolb's stages of concrete experience,[5] reflective observation, abstract conceptualization, and active experimentation. Cognitive load theory focuses on optimizing cognitive load during learning to enhance information retention. VR's interactive environments can reduce extraneous cognitive load by providing intuitive and realistic simulations, thus facilitating better learning outcomes.

The primary objectives of this study are to evaluate the differences in knowledge retention, practical skills development, student engagement, and readiness for professional practice between 2 cohorts of students—one using traditional physical simulations and the other employing a hybrid approach that incorporated VR. By addressing these objectives, this study aims to test the effectiveness of VR in educational settings and provide empirical evidence on its potential benefits.

To achieve these objectives, the primary research questions are:

- How do VR and physical simulations affect student learning and skill development throughout a 3-year degree program?
- How does the use of VR vs physical simulations affect the retention of theoretical knowledge throughout a 3-year degree program?
- How does the engagement level of students using VR compare with those using physical simulations during the course of their studies?
- Are students more satisfied with their learning experience when using VR compared with traditional physical simulations?
- How well prepared do students trained with VR feel for clinical practice compared with those who are trained with physical simulations?
- Are students who train with VR more adaptable to technological advancements in their field compared with those who only use physical simulations?

Understanding the differential effects of these teaching methodologies will substantially contribute to theoretical knowledge and practical applications. This study aims to augment the existing body of knowledge in educational psychology by providing empirical evidence on the effects of traditional physical simulations vs hybrid VR approaches on various learning outcomes. The authors sought to clarify how immersive learning environments influence cognitive processes, motivation, and retention, thereby advancing theories related to experiential learning and cognitive load. By examining student engagement and satisfaction across both methodologies, the study enhances the understanding of motivational factors in learning. Insights into how different approaches affect student motivation and cognitive load can help refine existing psychological theories and models.

For curriculum designers, the findings will inform the development of effective teaching strategies aimed at improving knowledge retention, practical skills development, and student engagement, whether through VR or traditional methods. This development can lead to the creation of more interactive and engaging learning materials tailored to diverse teaching methodologies. Furthermore, the study provides data-driven recommendations for integrating various teaching methods into training programs. Curriculum designers can leverage these insights to customize training modules that address the diverse needs and learning styles of students.

The study also offers valuable guidance for policymakers in education. Policymakers can use the study's findings to formulate policies that encourage the adoption of effective teaching methodologies. By demonstrating the comparative benefits of VR and traditional methods, the study can support policy initiatives aimed at modernizing education infrastructure and promoting digital literacy. In addition, the study provides evidence on the cost-effectiveness and education value of VR and traditional simulations, assisting policymakers in making informed decisions regarding resource allocation and investment in educational technology.

In preparing students for future professional challenges, the study will help to align teaching methods with technological advancements, ensuring that students are proficient in the use of modern technologies. This proficiency will better prepare students for the evolving demands of their professional fields, where technological competence is increasingly critical. The study objectively compares how immersive VR simulations and traditional methods can replicate real-world scenarios, thereby enhancing students' readiness for professional practice. This practical, hands-on experience is expected to equip students with the essential skills and confidence needed to excel in their careers, regardless of the methodology. Given the rapid pace of technological change in the professional landscape, the ability to adapt to new technologies is a vital skill. This study explores how different teaching methods, including VR, can enhance students' adaptability to technological innovations, emphasizing the importance of incorporating adaptive learning skills into educational curricula. By addressing these areas, the study provides comprehensive and unbiased insights that can drive improvements in education practices and policies, enhancing the overall quality of education and better preparing students for future challenges.

Methods

This longitudinal cohort study compared the educational outcomes of 2 cohorts of students throughout the entirety of their 3-year degree programs at a single institution.[6] The first cohort was exclusively taught using traditional physical simulation machines (Siemens). In contrast, the second cohort received instruction through a combination of VR technology (X-Ray Pro VR by Virtual Medical Coaching) and the same physical simulation machines. The primary objective of the study was to assess and compare the long-term effects of these teaching methodologies on various educational outcomes.

Given the natural progression in the availability of VR technology, the study inherently adopted a quasi-experimental design. The 2020 cohort, lacking access to VR technology, serves as a control group, allowing for an unambiguous comparison with the subsequent cohort that used VR and traditional methods. This setup ensured that any significant differences in educational outcomes between the cohorts can be attributed more directly to the introduction of VR technology, as there were no changes in instructor techniques or curriculum updates between these years.

Ethical Considerations

The study was approved by the Dr Sótero del Río Healthcare Complex Ethics Committee in Santiago, Chile (2019/3748). Informed consent was obtained from all participants before data collection. Participants were assured of their right to withdraw from the study at any time without penalty. All data were anonymized and securely stored to protect participants' confidentiality.

Participants

The study involved undergraduate students enrolled in a 3-year degree program at a single institution. The physical cohort ($N = 50$) used only physical simulation machines, while the hybrid cohort ($N = 65$), beginning in 2021, experienced a blended approach incorporating VR and physical simulations. Participants ranged in age from 18 to 25 years, with varying levels of previous experience with technology. All participants started the study in their first year of the radiography program, with none having previous experience in clinical settings. None of the participants were lost to follow-up throughout the study period.

The authors compared the 2 cohorts for baseline equivalence based on age, sex, ethnicity, and entrance exam scores. An independent samples *t* test was used for age ($P = .34$) and entrance exam scores ($P = .45$). A chi-square test of independence revealed no significant association between sex and cohort, ($\chi^2_1 = 0.18$, $P = .67$), or between ethnicity and cohort ($\chi^2_2 = 0.012$, $P = .99$). The analysis revealed no significant differences between the 2 groups in any baseline characteristics, with all *P* values exceeding the alpha level of .05, indicating that the cohorts were equivalent at the start of the study.

Inclusion Criteria

The inclusion criterion was enrolment in the specified degree program with a commitment to participate in the study for the duration of their degree.

Exclusion Criteria

Transfer students who did not begin their studies in the respective cohorts and students who withdrew from the degree program before completion were excluded from study participation.

Equipment and Simulations

The VR simulations were conducted using the Virtual Medical Coaching software, which includes a VR headset, hand controllers, and a computer. The simulations covered various radiographic procedures, including positioning, image acquisition, and patient interaction scenarios. The physical simulations were performed using Siemens ceiling-suspended machines, including a digital detector, a radiographic table including functioning Bucky, an erect detector, and anthropomorphic phantoms, which are widely used in radiography training programs. These simulations involved hands-on practice with phantoms and peer role-playing to replicate clinical procedures.

Before the study, participants received training on how to use the VR equipment and the physical simulation machines to ensure they were comfortable with the technology. This training included a 1-hour orientation session and a 2-hour practical workshop.

X-Ray Pro VR Suite was the software selected for this study because of several key features and benefits that distinguish it from other VR solutions available on the market. This software offers comprehensive radiographic simulations, providing a wide range of realistic procedures including positioning, image acquisition, and patient interaction scenarios, which are essential for radiography training. This comprehensive coverage ensures that students can practice a variety of skills in a single platform. The software is designed with a user-friendly interface, making it accessible to students with varying levels of prior experience with technology. This ease of use reduces the learning curve associated with adopting new technology in educational settings. In addition, the software provides high-quality graphics and realistic simulations that closely mimic real-world scenarios. This level of realism enhances the immersive experience, which is critical for effective learning and skill acquisition. Compared with other VR solutions, Virtual Medical Coaching offers a cost-effective option for education institutions. The software's pricing model and the ability to use existing VR hardware make it a financially viable choice for long-term implementation, with costs amounting to $5 per student per week based on a degree license. These costs were covered by the university and the students could use the software at home and on campus.

Previous studies and testimonials have demonstrated the effectiveness of Virtual Medical Coaching in improving student engagement, knowledge retention, and practical skills, supporting its use as a reliable tool for radiography training.[2,4,7,8] The company also provides robust support and training resources for educators and students, including comprehensive user manuals, tutorial videos, and responsive customer support, ensuring that users can maximize the benefits of the software. Unlike other software that the authors trialed (eg, MedSpaceVR, Ziltron, Shaderware, Simtics, Vitasim, CETSOL), Virtual Medical Coaching offers desktop and fully immersive VR experiences. This versatility allows for a more comprehensive training approach, enabling students to transition seamlessly between different learning environments and modalities. While CETSOL and Vitasim offer some VR functionality, they were not suited to the university's learning approach.

Data Collection

The data collection process involved administering quantitative surveys and standardized tests at key points throughout the study to gather comprehensive data on student performance, engagement, satisfaction with the simulations, and overall satisfaction with the degree program. The surveys were developed carefully to assess various aspects of student learning experiences and outcomes. They included a combination of validated instruments and custom-designed questions specific to this study. The validated instruments were chosen for their reliability and relevance to constructs such as motivation, engagement, and satisfaction.[9] Custom questions were designed to capture specific details related to the use of VR and physical simulations, ensuring relevance to the study.[10]

Survey Administration

Baseline assessments were conducted at the start of the degree program to establish initial levels of knowledge, motivation, and engagement. End-of-year assessments were administered at the end of the first and second academic years to measure changes and progress in student outcomes, including the results of practical tests conducted in hospital settings. Final assessments were performed at the end of the degree program to evaluate outcomes in terms of knowledge retention, practical skills, and readiness for professional practice, including evaluations by clinical tutors on career readiness and performance.

Student satisfaction with the degree program was measured through specific survey questions that asked students to rate their overall satisfaction with the program on a Likert scale, as well as to provide feedback on various aspects of the program (eg, course content, teaching quality, resources). This longitudinal approach allowed for the tracking of changes in student experiences and outcomes during a specific period, providing a dynamic view of the effect of various teaching methodologies.[11] The surveys included various question types to capture detailed quantitative information, such as Likert-scale questions to measure levels of motivation, engagement, and satisfaction, where students rated their agreement with statements such as "I feel motivated to learn using this method" on a scale from 1 (strongly disagree) to 5 (strongly agree),[11] and multiple-choice questions designed to assess knowledge retention and practical skills through scenario-based questions. The comprehensive survey design and strategic timing of administration ensured the collection of robust data to support the study's findings.

Data Analysis

Data were analyzed using mixed-effects models to account for intraindividual variability over time and interindividual differences between cohorts. This approach allowed authors to assess the fixed effects of the teaching methods on student outcomes while controlling for random effects such as variability in instructional quality and student backgrounds.

Analytical Strategies

Baseline characteristics, such as previous knowledge level, were controlled for in the models to adjust for initial differences between cohorts. Linear regression was used for baseline adjustment to control any initial differences, modeling the relationship between dependent and independent variables. Adjusting for these baseline characteristics allowed for more accurate assessments of the effects of the different teaching methods, enhancing the study's validity.

Sensitivity analyses were conducted to determine the effect of dropout rates on the study's findings, ensuring that the results remained robust despite any participant attrition. The threshold for significance was set at P less than .05, and all analyses were performed using the statistical software R version 3.6.1 (The R Foundation).

In addition, kernel density estimation (KDE) was used to analyze the distribution of student scores. KDE is a nonparametric method that estimates the probability density function of a random variable, creating a continuous probability density curve that provides a clearer visualization of score distributions. In this study, KDE was applied to visualize the distribution of posttest scores, practical exam scores, and career readiness scores across the 2 cohorts, helping to identify patterns and differences in score distributions that might not be evident from summary statistics alone.

Results

The mean posttest score for the hybrid cohort is 79.7%, which is significantly higher than the physical cohort's mean score of 69.2% ($P < .001$, see **Table 1** and **Figure 1**). In practical exams, the hybrid cohort demonstrated a mean score of 80.5%, exceeding the physical cohort's mean of 71.0% ($P < .001$). The career readiness score was derived from assessments conducted by clinical tutors at the end of each academic year. This score measures the students' preparedness for professional practice, including practical skills, theoretical knowledge, and overall performance in clinical settings. The career readiness score for the hybrid cohort averaged 80.3%, surpassing the physical cohort's average of 66.9% ($P < .001$). The internship performance score, with an average score of 79.6%, shows that the hybrid cohort outperformed the physical cohort's average of 69.9% in terms of internship performance ($P < .001$).

The hybrid cohort reported a higher mean motivation level of 4.7, compared with 4.3 for the physical cohort ($P < .001$, see **Table 2** and **Figure 2**). The mean engagement level was 4.7 for the hybrid cohort, significantly greater than the physical cohort's 3.6 ($P < .001$). Satisfaction scores from the third year further support the efficacy of the hybrid model, with the hybrid cohort

Table 1

Scores Comparison Between Hybrid and Physical Cohorts

Metric	Hybrid, mean	Physical, mean	*P* value
Posttest score, %	79.7	69.2	$<$ .001
Practical exam score, %	80.5	71.0	$<$ .001
Career readiness score, %	80.3	66.9	$<$ .001
Internship performance score, %	79.6	69.9	$<$ .001

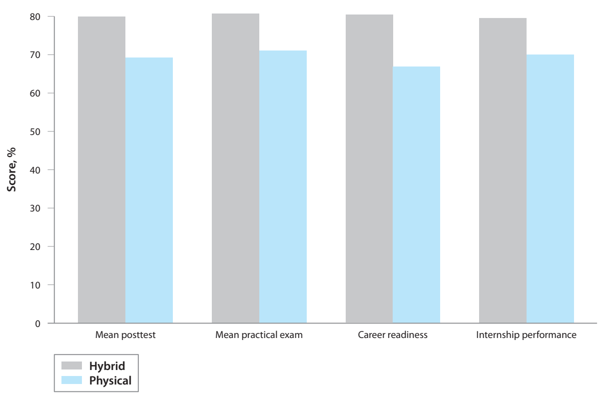

Figure 1. *A comparison between hybrid and physical cohorts regarding their mean posttest scores, mean practical exam scores, career readiness, and internship performance. The hybrid cohort consistently outperformed the physical cohort in academic and practical assessments. Figure courtesy of the authors.*

scoring an average of 4.7 compared with the physical cohort's 4.2 ($P = .002$).

Figure 3 offers a deeper dive into the distribution of the scores beyond the means. This figure presents the median scores and the range within which the middle 50% of scores lie, depicted by the boxes. The length of the whiskers and the presence of outliers provide additional context to the variability and range of scores in each cohort. The shorter box and shorter whiskers for the hybrid cohort indicate less variability in scores, suggesting a more consistent performance across students.

Figure 4 includes histograms overlaid with KDE lines for each cohort, offering a visual depiction of the score distribution density. The shape of the KDE curve indicates whether the scores are normally distributed, skewed, or have multiple peaks. The histograms also reveal how scores are spread across the performance spectrum, allowing readers to infer the proportion of students achieving high or low scores. For example, a right-skewed distribution for the hybrid cohort in the histogram shows that many students scored at the higher end of the scale.

Discussion

The mean posttest score was significantly higher for the hybrid cohort than it was for the physical cohort, showing strong evidence against the null hypothesis, suggesting that the observed difference is significant and indicates that the hybrid model might offer a more effective approach to academic learning. The practical exam mean score was significantly higher in the hybrid cohort compared with the physical cohort, highlighting the hybrid cohort's superior practical understanding and application. The hybrid cohort's career readiness was significantly higher than was the physical cohort's readiness. This metric is critical as it indicates the readiness of students to transition into their professional roles, highlighting the potential of the hybrid approach in preparing students for the job market more effectively. The internship performance score was significantly higher in the hybrid cohort compared with the physical cohort, showing a distinct advantage for the hybrid cohort, indicating that these students might have gained more from experiences directly applicable to professional settings.

The hybrid cohort reported a significantly higher mean motivation level compared with the physical cohort, suggesting that the immersive elements of hybrid learning might boost student motivation more effectively than with traditional methods. The mean engagement level was significantly higher than was

Table 2

Soft Skills Comparison Between Hybrid and Physical Cohorts

Metric[a]	Hybrid, mean	Physical, mean	*P* value
Motivation level	4.7	4.3	< .001
Engagement level	4.7	3.6	< .001
Satisfaction level	4.7	4.2	.002

[a] *Levels were measured on a Likert scale from 1 (strongly disagree) to 5 (strongly agree).*

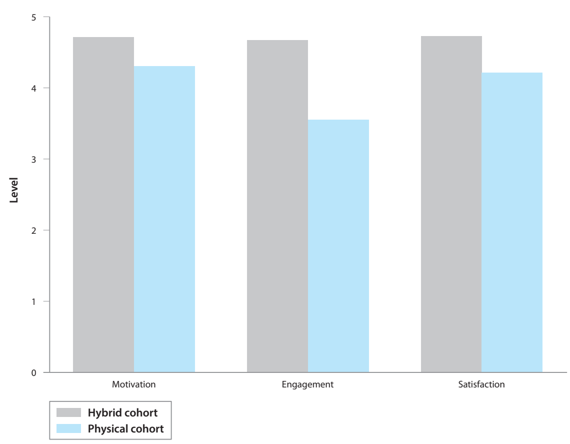

Figure 2. *Comparing mean levels of soft skills (motivation, engagement, and overall satisfaction) in the third year between the hybrid and physical cohorts. The hybrid learners reported significantly higher levels of motivation, engagement, and satisfaction. Figure courtesy of the authors.*

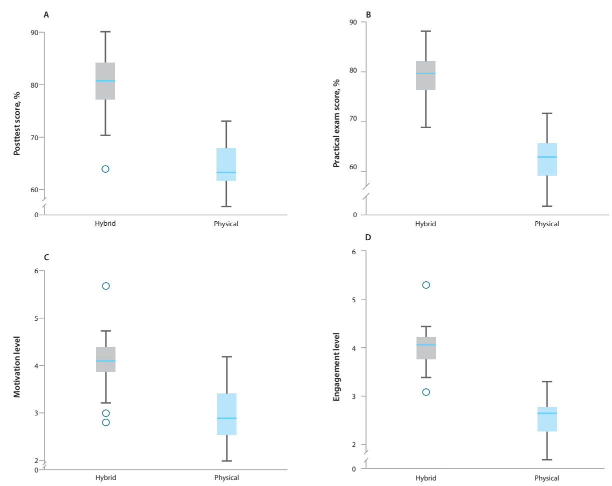

Figure 3. *Distribution ranges, medians, and outliers among hybrid and physical training cohorts in mean posttest scores (A), mean practical exam scores (B), mean motivation level (C), and mean engagement level (D). Figure courtesy of the authors.*

the engagement level of the physical cohort. This finding effectively demonstrates the greater engagement that hybrid learning seems to foster among students, a critical component in successful learning outcomes. The satisfaction scores from the third year scored significantly higher in the hybrid cohort compared with the physical cohort. This result might be attributed to the interactive and potentially more engaging nature of hybrid learning environments that cater to the preferences of contemporary learners.

Integrating VR into health care training and radiography education has been gaining traction because of its potential to enhance learning outcomes and student engagement.[12] The findings of this study underscore the significant advantages of integrating VR into traditional simulation-based curricula, which are particularly evident in the hybrid cohort's superior performance during the 3-year period.[13] These students consistently outperformed their peers in knowledge retention and practical skills assessments, as demonstrated by their higher scores in yearly posttests. In addition, the hybrid cohort reported heightened levels of engagement, motivation, and satisfaction, indicating a more enriching educational experience. The integration of VR not only enhances cognitive and skill-based learning outcomes but also improves affective elements, such as student engagement and satisfaction, thereby enriching the overall educational experience.

Students' increased engagement and satisfaction with VR-based training can be attributed to several factors, especially their familiarity and comfort with technology. Many of today's students, often referred to

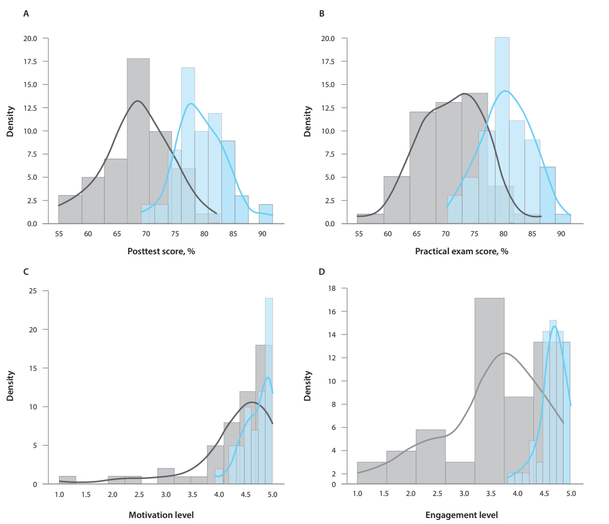

Figure 4. *The distribution and density estimation of scores of hybrid (blue) and physical (gray) training cohorts, showing the overall spread and kernel density estimation of mean posttest score (A), mean practical exam score (B), mean motivation level (C), and mean engagement level (D). Figure courtesy of the authors.*

as *digital natives*, have grown up with computers, video games, and various forms of technology, making them more adaptable to immersive learning environments like VR. This comfort with technology allows them to engage more deeply and naturally with VR simulations, which offer an interactive and experiential form of learning that traditional methods might lack.

The heightened engagement and satisfaction likely stem from the immersive nature of VR, which can make learning more dynamic and enjoyable. VR provides realistic scenarios where students can practice and hone their skills in a safe, controlled environment, allowing for repeated practice without the risks associated with real-life mistakes. This hands-on experience can lead to better knowledge retention and a deeper understanding of complex concepts, as supported by the findings of Vestbøstad et al and Kazu and Yalçın.[13,14]

These results align with previous research highlighting the benefits of immersive educational technologies. Studies by O'Connor and Rainford emphasized the effectiveness of VR in providing engaging and authentic learning experiences.[2] Similarly, Dede underscored VR's potential to offer immersive learning environments that traditional methods often struggle to provide.[3] Furthermore, these findings are consistent with Kazu and Yalçın and Mayer's multimedia learning theory, suggesting that well-designed multimedia instructions, such as those incorporating VR, can enhance learning outcomes by engaging multiple sensory pathways.[14,15] The superior performance of the hybrid cohort in this study might be attributed to the multimodal learning environment facilitated by VR, which complements physical simulations with visual and experiential depth.[16]

This study contributes to the experiential learning framework by demonstrating that hybrid simulation methods enhance the reflection and abstract conceptualization phases of Kolb's learning cycle.[5] These results advocate for the widespread integration of VR technologies in simulation-based learning curricula across disciplines. This especially is relevant for fields involving complex spatial or procedural knowledge, such as medicine, engineering, and natural sciences.[17,18]

The observed increase in engagement and satisfaction among students in the hybrid cohort also holds practical implications for educational design. Institutions might leverage these findings when designing curricula to enhance student retention and success rates. Higher engagement levels often are associated with higher academic achievement and lower dropout rates, indicating the potential of VR integration to improve student outcomes.

Limitations

The absence of random assignment to cohorts raises concerns about selection bias, although ethical considerations precluded the possibility of a randomized controlled trial. Conducting a randomized trial would have potentially compromised education quality for some students. In addition, the study's single-institution setting limits the generalizability of the results to other educational contexts. Methodologically, the study's timeframe coincided with rapid advancements in VR technology, which affected the consistency of instructional quality and student experience over time. Furthermore, subtle differences in cohort characteristics or external socioeconomic factors could influence outcomes, despite efforts to ensure comparability between cohorts.

Future Research Directions

Future research should explore controlled designs that do not compromise educational quality while investigating the longitudinal effects of VR integration in diverse academic settings. This includes examining effects on a broader range of outcomes, such as emotional and social skills, and determining the optimal balance between traditional and VR-based activities to maximize learning outcomes without inducing cognitive overload. Replicating this study across multiple institutions and contexts would further validate findings and enhance their applicability in educational practice.

Conclusion

This study provides compelling evidence for the effectiveness of hybrid VR and physical simulation-based curricula in enhancing student learning outcomes and educational experiences in a 3-year radiography program. By addressing theoretical, practical, and methodological considerations, these findings contribute to the broader discourse on the integration of immersive technologies in education, paving the way for future research and educational innovations.

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