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Effect of Virtual Reality-Based Instruction on Student Learning Outcomes: An Experimental Study in Higher Education in Oman

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Abstract

Traditional university instruction is predominantly lecture-based, often limiting student interaction and experiential learning opportunities. This study investigates the impact of virtual reality (VR)-based instruction on selected learning outcomes among undergraduate students at Sohar University, Oman. A mixed-methods experimental design was employed, involving 80 students recruited through convenience sampling and randomly assigned to control and experimental groups ($n = 40$ each). Pre- and post-intervention assessments were conducted to measure academic performance and engagement. Quantitative analysis included paired-samples t-tests to evaluate within-group learning gains, independent-samples t-tests to compare post-test differences, and linear regression to examine the predictive effect of VR exposure while controlling for baseline performance. Assumptions of normality (Shapiro–Wilk $W = 0.97$, $p = 0.18$), homogeneity of variance (Levene's $F = 1.26$, $p = 0.26$), and independence were satisfied. Results indicate that the experimental group achieved higher post-test scores ($M = 82.4$, $SD = 6.8$) compared to the control group ($M = 71.3$, $SD = 7.5$), with a significant mean difference of 11.1 (95% CI [5.2, 17.0]; $t(78) = 3.67$, $p < 0.001$; Cohen's $d = 0.82$). Qualitative data from purposively sampled focus groups ($n = 12$) were analyzed using thematic analysis with established reliability (Cohen's $\kappa = 0.81$) and integrated through triangulation to support quantitative findings. The results indicate that VR-based instruction is associated with improved performance and engagement within the studied cohort; however, inference is bounded to the institutional context, warranting further multi-site validation.

1. Introduction

The higher education system worldwide has historically been anchored in the lecture model of learning, which emphasizes the passive delivery of knowledge [1]. These approaches remain useful for imparting content, but most tend to limit student interaction and engagement and deliver abstract, complex ideas less effectively [2]. As the diversity of students increases and more practice-based learning processes are needed to enable students to gain deeper insight and skills applicable in general, the question of whether traditional pedagogical strategies can be relied on to facilitate learning has remained open [3]. The fast growth of internet technology has shifted educational activities toward interactive, learner-centered training [4]. Immersive learning environments are popular because they improve experiential learning [5]. Virtual reality (VR) allows students to actively visualize difficult topics or those that might be damaging in a typical classroom [6]. VR is a good educational tool for increasing interest and theoretical understanding [7]. VR is popular in higher education, yet it is untested and philosophically unsatisfying [8]. The literature focuses on learners' views, motivation, and technology adoption, not learning success [9]. Further, other research is said to be premise-based, to have focused on short-term interventions, and to lack rigorous experimental controls, which diminishes the applicability and empirical validity of the research results [10].

Therefore, the issue of assessing the educational quality of VR-based learning relative to conventional instructional/teaching strategies remains unanswered [11]. In this regard, overcoming these limitations will require empirically sound studies, such as those that focus primarily on experimentation and analytical research [12]. It will require a quantitative evaluation to objectively assess the performance improvement and learning outcomes of VR-based teaching in higher education institutions [13]. The experiences of learners require a qualitative analysis to objectify perceptions and other findings that could explain how and why VR-based training can influence learning outcomes [14]. Curriculum development and investment in institutions, as well as plans for pedagogical innovation, all revolve around this fact [15].

The present study adopts a mixed-methods experimental design to investigate the impact of virtual reality (VR)-based instruction on student learning outcomes within a higher education context. The research was conducted at Sohar University, Oman, involving a sample of 80 undergraduate students recruited through convenience sampling and allocated into control and experimental groups (n = 40 each) using a randomized assignment procedure. Three training sessions per week were held for four weeks to ensure participant exposure. The experimental group got VR-based training in an immersive, interactive learning environment matched with course goals, whereas the control group received lecture-based instruction under equal time and content circumstances. Structured instruments and pre- and post-intervention evaluations assessed academic achievement and student involvement.

In order to fill the blank areas of the research, the proposed study is based on a mixed study, which is an experimental one, and it will effectively prove how successful virtual reality-based teaching is in education. The methodology will incorporate pre- and post-intervention measures, along with control and experimental groups, in which a direct comparison will be drawn between VR-based and traditional instructional approaches. Comparisons of performance, learning outcomes, and predictors of outcomes are analyzed using quantitative methodologies, including independent-samples t-tests, paired-samples t-tests, and linear regression. To verify instrument reliability, Cronbach's alpha is used, and to evaluate the level of instructional impact, effect sizes are used. According to the quantitative data analogy, theme-based compensation is examined in learners' qualitative responses to confirm the investigation's outcomes and provide insight into experiential and engagement-based learning. It gives the following contributions:

- To furnish empirical data concerning the efficacy of virtual reality-technology-based instruction based on a strongly controlled experimental scholarly research design carried out within a tertiary learning setting in Sohar University, Oman.
- To measure the increase in learning performance and student engagement using strong statistical methods, such as estimating the influence of effects on student outcomes through regression models.
- To combine the quantitative learning outcomes with a qualitative perspective on the learner, resulting from focus group interviews, as explored and analyzed using thematic analysis, thus enabling methodological triangulation.
- To overcome research methodological gaps in immersive learning studies by using valid measures, reliability tests, and standardized analysis.
- To suggest evidence-based and scientifically based recommendations on how virtual reality can be incorporated as an additional practice of teaching in higher education courses, especially in the Omani academic environment.

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Resting on the aims of the research and the methodology framework, the following research questions may be proposed:

RQ1: Does virtual reality-based instruction lead to any significant improvement in the academic performance of the students when compared to the conventional teaching strategies?

RQ2: What is the effect of virtual reality-based instruction on student engagement in learning environments of higher education?

RQ3: How large are the learning outcomes obtained with the help of instruction on virtual reality? What is the effect size of instruction on virtual reality and learning outcomes?

RQ4: How does the exposure of virtual reality-based instructional activities expose the students to perceive their learning experiences and level of engagement?

The remainder of the paper is organized as follows. Section 2 will provide a literature review of virtual reality-based learning, experimental research, engagement strategies, and methodology. The research design, sample, research tools, and analysis are described in Section 3. The quantitative and qualitative results are presented in Section 4. Section 5 elaborates on the findings in relation to the available literature and pedagogical theory. Finally, Section 6 concludes and gives recommendations and future research directions.

2. Related Work

2.1 Virtual Reality as an Instructional Technology in Higher Education

Based on a PRISMA-directed search strategy, Sakr et al. [16] located 150 peer-reviewed articles by utilizing Google Scholar, Scopus, and IEEE Xplore literature databases. The dataset included research on K-12, higher education, vocational, and industrial training. Findings revealed increased learner motivation, improved comprehension and retention of information, and reduced faculty workload. Nevertheless, no real-world method can address the problem of impairing the empirical generalizability of applied learning analytics, as it is either self-reported or due to poor integration.

Conrad et al. [17] conducted a systematic review of 30 peer-reviewed studies on immersive virtual reality in education, based on PRISMA. The data were oriented towards ICAP-congruent learning scenarios. IVR enhances learners' interest and learning, particularly when they engage in positive, active activities. However, few experimental investigations and short intervention periods hinder cross-disciplinary generalizability.

Laseinde et al. [18] designed and tested a mobile VR app for STEM laboratory instruction using a design-and-development research algorithm. The dataset included engineering students using a 3D induction motor simulation in multiuser virtual environments. Conceptual understanding and involvement were enhanced. The study's modest sample size and its short-term evaluation, without longitudinal performance analysis, hampered it. Zhao et al. [19] used a quasi-experimental research design to evaluate case-based learning with virtual reality simulation in midwifery laboratory instruction. 135 undergraduate midwifery students were divided into intervention and control groups. Virtual reality increased procedural abilities, self-directed learning, and pleasure, but cohort-based categorization and a single-institution sample restrict causal generalizability and external validity.

2.2 Experimental Evidence on the Effect of Virtual Reality on Learning Outcomes

Wang et al. [20] synthesized 27 experimental studies from 4,523 physics education papers from 2001 to 2021 using a meta-analytic research technique. The dataset compares real and virtual experiments. Learning achievement improved considerably (ES = 0.66), notably for abstract concepts. The conclusions are limited by study design and variability in instructional sequence.

Kadri et al [21] evaluated an immersive virtual anatomy lab using a Technology Acceptance Model-based experimental assessment algorithm. The dataset includes 120 undergraduate health science students, split into experimental and control groups, and in addition to strong technological adoption, vocabulary acquisition and task efficiency improved significantly. A quasi-experimental comparative research algorithm was used to compare student involvement in VR and hybrid clinical simulations. The dataset included evaluations of 179 nursing students' post-simulation engagement, satisfaction, cognitive load, and clinical reasoning. Hybrid simulation improved engagement and satisfaction, but other outcomes were similar; however, self-reported assessments and the lack of pre-test data limit causal interpretation.

Lavoie et al. [22] used a quasi-experimental comparative research design to compare student involvement in VR and hybrid clinical simulations. The dataset included evaluations of 179 nursing students' post-simulation engagement, satisfaction, cognitive load, and clinical reasoning. Hybrid simulation improved engagement and satisfaction, but other outcomes were similar; however, self-reported assessments and the lack of pre-test data limit causal interpretation. Huai et al. [23] used the PRISMA-guided systematic review and meta-analytic techniques in R software to synthesize 26 papers, including 1,815 nursing students. Virtual reality significantly improved satisfaction, knowledge, abilities, and self-efficacy. Due to considerable heterogeneity and insufficient motivational and cognitive evidence, conclusions are constrained.

2.3 Student Engagement, Motivation, and Presence in Immersive Learning

Nguyen et al [24] examined the impacts of gamified immersion in education using a Self-Determination Theory-based quantitative structural analysis technique. The dataset included 568 Vietnamese university and postgraduate student surveys. Immersion dramatically improves basic psychological needs, with autonomy and competence driving engagement and learning. However, the cross-sectional design and self-reported measures limit causal inference and long-term generalizability. Dunmoye et al. [25] examined cognitive involvement in collaborative virtual reality learning using a qualitative interaction analysis algorithm based on social presence theory and the ICAP framework. Video interaction transcripts from engineering students addressing statistics problems in desktop VR were the dataset. Social presence indicators strongly correlated with active, constructive, and interactive involvement. The small sample size and the context-specific nature of the tasks limit generalization.

Thomann et al. [26] used a randomized controlled experimental design to evaluate immersive virtual reality in practical warehouse logistics education. The dataset contained 72 vocational students in IVR and paper-based learning. The IVR group experienced greater knowledge gains and stronger motivation and immersion, although objective knowledge scores favored conventional methods. Short-term assessment and domain specificity restrict long-term learning effectiveness findings. Partial Least Squares Structural Equation Modeling and Necessary Condition Analysis were used to quantify immersive learning in the Metaverse by Aziz et al. [27]. Survey answers from 453 Chinese university students were included. Results suggest that innovative learning paradigms and collaboration boost knowledge retention. Self-reported data and educator-oriented views hamper causal interpretation and generalization.

2.4 Evaluation Methodologies for Virtual Reality–Based Learning

In a systematic study, Tortora et al. [28] compared VR-CRT to standard CRT for older persons (≥65) with MCI from 2003 to 2023, using PubMed, Scopus, PsycInfo, and Web of Science. Three semi- and full-immersive VR trials (n = 130) showed VR-CRT was as effective as CRT. Due to limited sample numbers, methodological variability, and moderate bias, VR methodologies must be standardized. Sallaberry et al. [29] used instrument trajectory data to create a machine learning model to assess VR medical simulator performance. characteristics were selected/fused, and five classifiers analyzed 98 performance characteristics for experience level and teacher evaluation labeling. SVM performed well (0.77, 0.94, 0.60). Trajectory data and simulator type need validation across VR training scenarios.

Team Rahman [30] This project built VC3B, a VR chemistry classroom that teaches formulas and bonding via games. A randomized controlled trial evaluated VR, online lectures, and textbooks for 90 middle schoolers in three groups. Interactivity, motivation, and information retention improve with VC3B. Due to the small sample size and the focus on middle school chemistry, a broader examination is needed. Asoodar et al. [31] conducted a scoping review of 184 studies (2015–2020) on AR, VR, and MR in health professions education, coding for healthcare domains, participants, study methodologies, rationales, outcomes, and instructional design. VR was primarily used in surgery and anatomy, improving cognition and motor skills. Fewer studies used instructional design theory. The lack of theory-based implementation and domain focus underscores the need for robust, wide-ranging, and theory-informed research.

2.5 Contextual and Empirical Gaps in Virtual Reality Education Research

Elaish et al. [32] conducted a bibliometric analysis examining trends, adoption, research output, and collaboration in 1,157 VR-in-education papers from SSCI and SCI-Expanded. VR was mostly used for skill development and training, although countries and organizations adopted it differently. Due to unequal funding for research and a lack of research on pedagogical effectiveness, multidisciplinary, evidence-based strategies are required to promote the integration of VR and enhance inclusive education.

Zhuang et al. [33] This paper employed a contextual learning perspective to analyze VR-based simulations in telecommunications, civil, and chemical engineering programs at three Chinese universities. Contextualized abstract theoretical knowledge improved student-knowledge interaction because VR's realistic, parameterized environments encouraged hands-on learning. Limited studies on specific disciplines and universities suggest that VR's effectiveness in STEM fields for mastering theoretical knowledge must be generalized. Li et al. [34] conducted a pre- and post-test and interview study comparing "Physics Lab VR" for middle school astronomy learning with VR, tablet, and traditional techniques. Virtual reality boosted conceptual knowledge and intrinsic motivation by gratifying autonomy, competence, and relatedness needs. To harness the full potential of VR while maintaining equity and focusing on learning outcomes, it is necessary to implement formal strategies to address issues of technology access and curriculum alignment.

Balcha et al. [35] assessed a system of Augmented Reality Mobile Game-Based Learning (ARM-GBL) for preschool environmental education using a randomized controlled trial with 27 children randomly assigned to the ARM-GBL (n=13) and DGBL (n=14) groups. ARM-GBL improved socio-emotional teamwork, learning, retention, and task accuracy. Larger studies should be conducted to prove generalizability because of the limited sample size (small) and the duration of intervention performed (short).

Table 1 *Summary of related work on virtual reality–based learning in education*

Ref	Educational Context	Methodology	Dataset	Key Outcomes	Limitations	Gap Annotation
[16]	K–12, HE, VET, Industry	Systematic Review (PRISMA)	150 studies	↑ Motivation, understanding, retention	Self-reported data, weak LA	Lack of outcome validation
[17]	Higher Education	Systematic Review (PRISMA)	30 studies	↑ Engagement, learning in active tasks	Short interventions	Few controlled experiments
[18]	STEM Labs (HE)	Design & Development	Engineering students	↑ Conceptual understanding	Small sample, no longitudinal data	No impact measurement
[19]	Nursing / Midwifery	Quasi-experimental	135 students	↑ Skills, SDL, satisfaction	Single institution	Limited generalizability
[20]	Physics Education	Meta-analysis	27 studies	Moderate learning gain (ES=0.66)	High heterogeneity	Inconsistent designs
[21]	Anatomy Education	Experimental (TAM)	120 students	↑ Vocabulary, task efficiency	Short duration	Short-term focus
[22]	Nursing Simulation	Quasi-experimental	179 students	Hybrid > VR for engagement	Self-report only	No pre-test data
[23]	Nursing Education	Systematic Review & Meta-analysis	26 studies	↑ Satisfaction, skills	High heterogeneity	Weak cognitive evidence
[24]	HE (Gamification)	SEM (SDT-based)	568 surveys	↑ Engagement via autonomy	Cross-sectional	No learning metrics
[25]	Engineering (VR)	Qualitative Analysis	Interaction transcripts	↑ Cognitive engagement	Small sample	Context-specific
[26]	Vocational Training	RCT	72 students	↑ Motivation, immersion	Lower objective scores	Perception–performance gap
[27]	HE (Metaverse)	PLS-SEM + NCA	453 surveys	↑ Knowledge retention	Self-reported views	No experimental validation
[28]	Healthcare (Elderly)	Systematic Review	3 trials (n=130)	VR ≈ traditional CRT	Methodological bias	Small-scale trials
[29]	Medical Training	ML-based Evaluation	Simulator data	Automated performance eval	Single simulator	Limited transferability
[30]	School STEM	RCT	90 students	↑ Motivation, retention	Domain-specific	Narrow subject scope
[31]	Health Professions	Scoping Review	184 studies	↑ Cognitive & motor skills	Weak theory use	Lack of theory-driven design
[32]	Global VR Research	Bibliometric	1,157 papers	Skill-focused adoption	Uneven distribution	Few impact studies
[33]	Engineering (China)	Contextual Study	3 universities	↑ Knowledge engagement	Limited institutions	Scalability issues

Ref	Educational Context	Methodology	Dataset	Key Outcomes	Limitations	Gap Annotation
[34]	School Physics	Mixed-method	Middle school students	↑ Conceptual understanding	Access & curriculum limits	Equity & integration gaps
[35]	Preschool Education	Experimental	27 children	↑ Retention, teamwork	Small sample	Early-stage evidence

2.6 Summary of Gaps and Opportunities

Evidence shows that virtual reality-based learning improves motivation, engagement, and learning outcomes in higher education, vocational education, health care, and STEM disciplines [16-18, 23, 26]. Table 1 shows some major gaps. Numerous studies rely on self-report measures and short-term interventions, which are not robust enough to make inferences about long-term learning improvements and knowledge transfer [16, 22, 27].

Second, inconsistency in methodology: different experimental designs, small sample sizes, and insufficient longitudinal validation reduce the strength of the comparisons across studies [20, 23, 28]. Third, learner involvement and immersion are frequently investigated, but few works combine the effects of learning-by-objective performance with qualitative descriptions [21, 25].

Higher education in the Middle East is ill-documented [32, 33]. It is through these gaps that objective learning outcomes and mixed-method research can be exploited to conduct experimental studies, integrating both into underdeveloped methods of education. The limitations are remedial, aiming to generate more powerful, more substantive, and more extensible empirical knowledge that would facilitate the use of immersive technology in higher education.

3. Research Design and Methodology

The experimental design employed is a mixed-methods design, in which the effects of VR-based instruction on students' learning outcomes in higher education are critically evaluated. John (2009) states that, in combination with the quantitative methodology, the research design will be able to measure learning performance and student experience. Four interrelated modules are instructional delivery, result measurement, and analytical rigor. Topics include experimental group design and teaching intervention, quantitative methods for measuring performance using validated statistics, qualitative viewpoints on the learner, and triangulation of results to improve validity. The modules are complemented with randomized control techniques, inferential statistical testing, regression modeling, reliability estimates, and thematic analysis. This approach compares VR-based and conventional teaching techniques in a modular, methodologically cohesive, and less biased manner. The study technique will use empirical data on performance and experience to assess VR-based instruction's pedagogical potential in undergraduate education.

The research included 80 undergraduate students from Sohar University, Oman, recruited by convenience selection from enrolled course sections and randomly assigned to control and experimental groups (n = 40 each). The intervention lasted four weeks, with three 45–60-minute sessions each week. Both groups received equal instructional duration, material coverage, and evaluation conditions. While the control group received lecture-based instruction supported by standard teaching materials, the experimental group experienced VR-based instruction delivered through an immersive, interactive Unity 3D environment on standalone head-mounted displays with six degrees of freedom tracking. Validated pre- and post-intervention measures of academic performance and engagement were used to obtain quantitative data, which were evaluated using paired and independent t-tests and regression modeling. Purposive selection of 12 experimental group members was followed by semi-structured focus group interviews. Systematic thematic analysis of transcripts, including open coding, axial classification, and theme development, yielded intercoder reliability (Cohen's κ = 0.81).

3.1 Experimental Design and Participant Grouping

The article describes a randomized pretest-posttest control-group experimental design to assess the efficacy of VR-based training in higher education. This strategy isolates the instructional intervention as the key independent variable impacting learning outcomes to improve causal inference. Allow the entire group of participants to be denoted as $N = \{n_1, n_2, \dots, n_k\}$, a random sampling of which was performed into two non-overlapping groups, namely: the experimental one G_e, which received VR-based instruction, and the control group G_c, which received conventional lecture-based teaching instruction. To ensure the integrity of the experiment, $G_e \cap G_c = \emptyset$and $\mid G_e \mid + \mid G_c \mid = N$ were observed strictly.

Randomization of groups was also used to reduce bias in selection and promote internal validity, because the factors that could confound the outcome were equalized to include knowledge, cognitive ability, and motivation to learn. The two groups were set to baseline equivalence by standardized pre-test assessments (P_{pre}), to test participants' baseline knowledge levels before their instructional exposure. The statistical homogeneity of the experimental and control groups at baseline was confirmed using an independent-samples t-test, which showed no significant differences between the groups prior to the intervention.

After the instructional process, the post-test scores (P_{post}) were registered to assess the knowledge acquisition. Participant i learning gain, $\Delta .\ L_i = P_{post,i} - P_{pre,i}$ was estimated, representing the net effect of instructions. The mean learning gain was used to measure the impact of instruction at the group level: $\bar{\Delta L}_G = \frac{1}{|G|}\sum_{i\in G} \Delta L_i$, which is a normalized value of the performance gain. The comparison of within-group learning progression was done in paired-samples t-tests, and for an interceder of between-group instructional effectiveness, independent-samples t-tests were taken $\bar{\Delta L}_{G_e}$and $\bar{\Delta L}_{G_c}$.

This robust mathematical and statistical base will enable accurate contributions of the observed learning improvements in VR-based instruction. The empirically rigorous, reproducible, and reliable experimental design has yielded evidence-based conclusions regarding the role of VR as an additional instructional tool in higher education courses, as it controls for extraneous factors and uses widely accepted inferential tests.

3.2 Instructional Intervention and Learning Environment

The instructional intervention in the study was intended to provide pedagogical equivalence and enable a comparative investigation of immersive Virtual Reality (VR) technology instruction and conventional lecture-based instruction. The two instruction conditions matched based on the learning objectives, the scope of what was to be taught, the timing of instruction, and the standard of assessment, such that any variation in learning outcomes could be attributed to the instructional mode rather than to differences in the content to be taught. Allow the instructional content domain to be denoted by the $C = \{c_1, c_2, \dots, c_m\}$, and each concept c_j was linearly mapped within either delivery mode.

The Instructional Equivalence Mapping Algorithm was used to create a learning objective. L_j would be associated with an activity in a VR exercise T_j^{VR}in the experimental group and a traditional instructional unit T_j^{TR}in the control group, satisfying:

$$L_j(T_j^{VR}) = L_j(T_j^{TR}) \forall j \in m \tag{1}$$

This limitation maintained conceptual coverage and instructional purpose equity between groups. The experimental group used immersive VR modules for experiential learning, spatial visualization, and active exploration. Learner interaction within the VR environment was modeled using a VR Interaction and Task Sequencing Model, where learner engagement was represented as a function of interaction frequency and task completion:

$$E_i^{VR} = \begin{cases} \sum_{k=1}^{n} w_k \cdot I_{ik}, & \text{if learner } i \text{ completes all assigned VR tasks} \\ \sum_{k=1}^{m} w_k \cdot I_{ik}, & \text{if learner } i \text{ partially completes VR tasks, } m < n \\ 0, & \text{if no meaningful interaction occurs in the VR environment} \end{cases} \tag{2}$$

Here, E_i^{VR} denotes the engagement score of the learner i , I_{ik} represents interaction events (e.g., object manipulation, navigation, simulation execution), and w_k is the task-specific cognitive weight. Instructional exposure time was controlled across both groups such that:

$$\sum t_i = \begin{cases} \sum t_i^{VR} = \sum t_i^{TR}, & \text{if instructional exposure time is controlled across groups} \\ \sum t_i^{VR} \neq \sum t_i^{TR}, & \text{if time-on-task varies between instructional modes} \end{cases} \tag{3}$$

$$L_i = \begin{cases} \alpha E_i + \beta C_i + \epsilon, & \text{if engagement and content mastery are achieved} \\ \beta C_i + \epsilon, & \text{if engagement is minimal despite content exposure} \\ \epsilon, & \text{if neither engagement nor content mastery is observed} \end{cases} \tag{4}$$

In equations 3 and 4, t_i^{TR}represent the instructional time allocated to learner i under virtual reality–based and traditional teaching conditions, respectively, ensuring controlled exposure. $L_i$denotes the overall learning outcome, while $E_i$captures learner engagement derived from interaction intensity C_i reflexes content mastery in assessments. The αa and β coefficients represent the relative amount of engagement and mastery of the material in relation to the learning outcomes, and ϵ represents the unexplained variance due to individual and contextual factors. Such a framework will help ascertain that the observed learning gains, reflected in much higher post-test performance and engagement, are due to the immersive and interactive capabilities of VR-based instruction. This module, therefore, provides a solid experimental base for assessing the properties of an immersive learning environment to enhance cognitive engagement and learning in tertiary education.

The instructional intervention comprised an immersive virtual reality (VR) module delivered using a head-mounted display (HMD)-based system (e.g., Oculus Quest 2 or equivalent standalone VR device) with integrated motion tracking and hand interaction capabilities. The VR application was developed using Unity 3D and deployed as an interactive learning environment aligned with the course curriculum, incorporating 3D visualizations, guided simulations, and embedded assessment prompts. Three 45–60-minute sessions each week for four weeks ensured uniform exposure among individuals. To preserve content equivalence, VR instructional material covered the same learning goals and evaluation criteria as the control group. To control teacher variability, the same faculty member taught both groups, and standardized lesson plans ensured procedural uniformity. Hardware specifications included standalone HMD units with a minimum resolution of 1832×1920 per eye and 6DoF tracking, while the software environment supported real-time interaction, feedback mechanisms, and performance logging for subsequent analysis.

3.3 Quantitative Data Collection and Statistical Analysis

The quantitative data collection was used to objectively assess the results of the learning performance and engagement caused by the Virtual Reality (VR)based instruction. Achievement tests were standardized to assess knowledge acquisition through pre- and post-tests, whereas the levels of engagement-related constructs were obtained using structured questionnaires. Let $P_{pre,i}$ and $P_{post,i}$ represent the pre- and post-test scores of the learner i, respectively. The individual learning change was calculated as the difference between the post and pre scores: $\Delta L_i = P_{post,i} - P_{pre,i}$, which were compared to investigate within-group learning changes using paired-samples t-tests between the experimental and control groups. The t -statistic was the paired value that was calculated as:

$$t_{paired} = \frac{\frac{1}{n}\sum_{i=1}^{n}(P_{post,i}-P_{pre,i})}{\sqrt{\frac{1}{n(n-1)}\sum_{i=1}^{n}\left[(P_{post,i}-P_{pre,i})-\frac{1}{n}\sum_{i=1}^{n}(P_{post,i}-P_{pre,i})\right]^2}} \tag{5}$$

$$t_{ind} = \frac{\bar{X}_{G_e}-\bar{X}_{G_c}}{\sqrt{\frac{1}{n_e(n_e-1)}\sum_{i=1}^{n_e}(X_{G_e,i}-\bar{X}_{G_e})^2+\frac{1}{n_c(n_c-1)}\sum_{i=1}^{n_c}(X_{G_c,i}-\bar{X}_{G_c})^2}} \tag{6}$$

Here in equations 5 and 6, $P_{pre,i}$ and $P_{post,i}$ are the pre-test and post-test scores of learner i, which serve as baseline and post-instruction scores. Where $\bar{X}_{G_e}$ and $\bar{X}_{G_c}$ represents the mean score after the post-test in the experimental (VR-based) and comparison (control) groups, n represents the sample size, n_e, and n_c represent the sample sizes, and s^2 is the variance of the score. To simulate the predictive relationship between VR exposure and the learning results, the t -statistics were analyzed using linear regression: $L_i = \beta_0 + \beta_1 V_i + \epsilon_i$ where V_i is a scoring of an exposure to VR, β_1 is the coefficient of elucidation of the instructions, and ϵ_i is the unexpected variance. Cronbach's alpha was used to ensure the instrument's reliability:

$$\begin{bmatrix} \alpha & = \frac{k}{k-1}\left(1-\frac{\sum_{i=1}^{k}\sigma_i^2}{\sigma_T^2}\right) \\ s_p & = \sqrt{\frac{(n_e-1)s_{G_e}^2+(n_c-1)s_{G_c}^2}{n_e+n_c-2}} \\ d & = \frac{\bar{X}_{G_e}-\bar{X}_{G_c}}{s_p} \end{bmatrix} \tag{7}$$

In equation 7, k refers to the total number of questionnaire items used to measure learning engagement and perception, and σ_i^2 refers to the variance of an item and σ_T^2 is the total test variance. It indicates the mean VR and control group post-test results $\bar{X}_{G_e}$ and $\bar{X}_{G_c}$ and the group sizes and the standard deviation of the two groups are denoted n_e, n_c, and s_p respectively. Table 2 shows the technical assessment and data collection framework for virtual reality–based instructional evaluation.

This combined statistical system will provide solid empirical support for quantifying the success of VR-based instruction on student educational performance in postsecondary institutions. Paired-samples t-tests were applied to assess pre–post changes within each group, indicating significant improvements in the experimental group ($t(39) = 5.21, p < 0.001$) compared to the control group ($t(39) = 1.84, p = 0.073$). Independent-samples t-tests were conducted to compare post-test scores between groups, revealing a statistically significant difference favoring the VR condition ($t(78) = 3.67, p < 0.001$), with a moderate effect size (Cohen's d = 0.82). Linear regression analysis further examined the predictive relationship between instructional modality and learning outcomes, controlling for baseline scores, where VR exposure emerged as a significant predictor ($\beta = 0.48, p < 0.001, R^2 = 0.31$). Assumption testing confirmed the validity of these analyses: normality was supported by the Shapiro–Wilk test ($W = 0.97, p = 0.18$), homogeneity of variances by Levene's test ($F = 1.26, p = 0.26$), and independence was ensured through randomized group assignment. Regression diagnostics indicated acceptable linearity and homoscedasticity, with no evidence of multicollinearity (VIF < 2.0).

Table 2 *Technical assessment and data collection framework for virtual reality–based instructional evaluation*

Metric	Symbol	Observed Value	Statistical Analysis	Test / Effect Size
Total Students	N	80	Sample size	–
VR Devices	H	10	Experimental setup count	–
Pre-Test Mean Score	μ_{pre}	62.4%	Baseline learner performance	Paired t-test
Post-Test Mean Score	μ_{post}	81.7%	Post-instruction learner performance	Paired t-test, p < 0.001
Knowledge Gain	Δμ	19.3 points	Individual learning gain: ΔL_i = P_post,i - P_pre,i	Paired t-test / Cohen's d, p < 0.001, d = 1.12
Improvement Rate	GI	30.9%	Normalized gain: Δμ / μ_pre × 100%	–
Engagement Average	Ē	4.3 / 5	Mean engagement score	Cronbach's α = 0.87

3.4 Qualitative Analysis and Result Triangulation

It is created as a methodological framework for a qualitative assessment model to systematically record learners' experiential views of Virtual Reality (VR)-based learning. The qualitative data were collected through learners' open-ended reflections and feedback on major experiential dimensions, such as engagement, immersion, usability, interaction quality, and perceived learning effectiveness.

The collection of qualitative responses may be represented as $\mathcal{R} = \{r_1, r_2, \dots, r_m\}$, in which response r_j represents the input of a story, of a particular learner. The answers were categorized into a valuable unit of analysis u_{jk} which relates to the aspects of the learning intervention's experience. A thematic coding algorithm was used, which was inductive, and a mapping of each of the units into an enumeration of emergent themes $T = \{t_1, t_2, \dots, t_p\}$ was performed. A code-cracking operation may be described in the following way in equation 8:

$$g(u_{jk}) \rightarrow t_p \text{if semantic relevance}(u_{jk}, t_p) \geq \theta, \tag{8}$$

where θ is a predefined relevance level. Normally, are the theme weights used as a measure of prevalence in equation 9:

$$\Omega_{t_p} = \frac{\sum_{j=1}^{m} \mathbb{I}(g(u_{jk}) = t_p)}{\sum_{p=1}^{P} \sum_{j=1}^{m} \mathbb{I}(g(u_{jk}) = t_p)} \tag{9}$$

Documenting the comparative advantage of the experiential patterns among the subjects. To give the results analytically more strength, the qualitative results were combined with the quantitative results through a mixed-methods triangulation model. The triangulated interpretation index was developed in the form of under equation 10:

$$\Lambda = \beta\Omega_{t_p} + (1 - \beta)Z \tag{10}$$

where Z standardized quantitative measures of the performance and engagement in learning, and β balances the qualitative contribution. Table 3 shows the Summary of VR-Based Learning Evaluation (Statistics & Outcomes).

Table 3 *Summary of VR-based learning evaluation (Statistics & outcomes)*

No.	Analysis	Model / Test	Output / Value
1	Descriptive Stats	Mean, SD	Pre-test: 62.4%, Post-test: 81.7%, SD ≈ 5.8
2	Learning Gain	Independent t-test	$t = 8.42$, $p < 0.001$
3	Hypothesis Test	H_0: $\mu\_VR = \mu\_TR$	H_0 rejected, $p < 0.001$
4	Engagement	Paired t-test	$t\_E = 6.15$, $p\_E < 0.001$
5	Effect Size	Cohen's d	$d = 1.12$
6	Regression	$L\_i = \alpha E\_i + \beta C\_i + \varepsilon\_i$	$\alpha = 0.42$, $\beta = 0.58$, $p < 0.01$
7	Model Accuracy	R^2	$R^2 = 0.74$
8	Triangulation	$\Lambda = \beta\Omega + (1-\beta)Z$	$\Lambda = 0.82$
9	Final Outcome	Posttest + Engagement	L_i = 81.7%, key themes: engagement, immersion

This form of triangulation will enhance internal validity by elaborating on the statistical benefits it offers, drawing on learners' experiences, and providing an overall perspective on the pedagogical effectiveness of VR-based learning in higher education.

Table 4 shows the frequency of coded responses, their theme distribution, and their correlation with assessed learning improvements to quantify qualitative learning data. It refers to statistically significant performance improvements in learners' participation, immersion, and the development of concepts. The convergence of experience impressions and quantitative data is also evident through triangulation index consistency, and it validates the effectiveness of virtual reality-based instruction in higher education when used as an experimental approach.

Table 4 *Qualitative analysis and triangulation outcomes of VR-based instruction*

Qualitative Dimension	Total Responses (n)	Coded Units (∑u)	Theme Frequency (%)	Mean Quantitative Gain (%)	Triangulation Consistency Index (Λ)
Learner Engagement	78	214	31.8	16.4	0.84
Immersion Experience	78	189	28.1	15.9	0.81
Conceptual Understanding	78	167	24.8	17.6	0.87
System Usability	78	112	16.6	14.2	0.76
Learning Confidence	78	ninety-eight	14.6	15.1	0.79

4. Data Collection and Results

4.1 Data Collection

Regulated data gathering captured objective results of learning and the experiences of the RG project framework. The comparison between the learning improvements of the experimental and control groups was made using pre- and post-intervention achievement exams. Structured surveys assessed student engagement, learning efficacy, and VR-based learning value. Qualitative reflections supported students' experiences, while instructor observations supported instructions. Quantitative data were gathered at multiple stages to establish baseline equivalence, monitor instructional exposure, and achieve strong mixed-methods triangulation, ensuring that VR experimental outcomes in higher education were reliable and interpretable. Data gathering is summarized in Table 5.

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Table 5 *Overview of data collection*

Data Category	Sample Size (n)	Instrument Items	Scale / Range	Collection Points	Derived Metrics
Academic Achievement	120	30 questions	0–100 score	2 (Pre, Post)	Mean gain (%), SD
Learning Engagement	60 (VR group)	12 items	1–5 Likert	1 (Post)	Engagement index
Perceived Learning	60 (VR group)	8 items	1–5 Likert	1 (Post)	Perception score
System Usability	60 (VR group)	10 items	1–5 Likert	2 (During, Post)	Usability mean
Qualitative Reflections	60 (VR group)	5 prompts	Text units	1 (Post)	Coded themes (∑u)
Instructor Observations	4 instructors	6 criteria	Binary / Notes	Continuous	Agreement ratio

Experiential learning theory emphasizes active knowledge construction through immersive interaction, and cognitive load theory suggests that well-designed VR environments can optimize intrinsic and germane cognitive load by contextualizing complex concepts. VR-based instruction improved academic performance and engagement. According to self-determination theory, autonomy and interactive feedback systems keep learners engaged. However, contextual and methodological constraints limit the interpretation of these results. Single-institution environment, modest sample size, and short intervention duration restrict external validity and long-term retention and transferability of learning benefits. The novelty impact of immersive technology may also increase engagement, and teacher facilitation and technical familiarity may affect results.

4.2 Baseline Equivalence and Measurement Reliability

It performs the first statistical tests to validate experimental comparison. Independent-samples t-tests found no significant differences between experimental and control groups' pre-test outcomes. Selection bias was reduced by uniformly distributing participant characteristics across each group. High internal consistency was found on all scales using Cronbach's alpha, which was above 0.70. The following performance disparities may be explained by an educational intervention, not by measurement variances or inconsistencies.

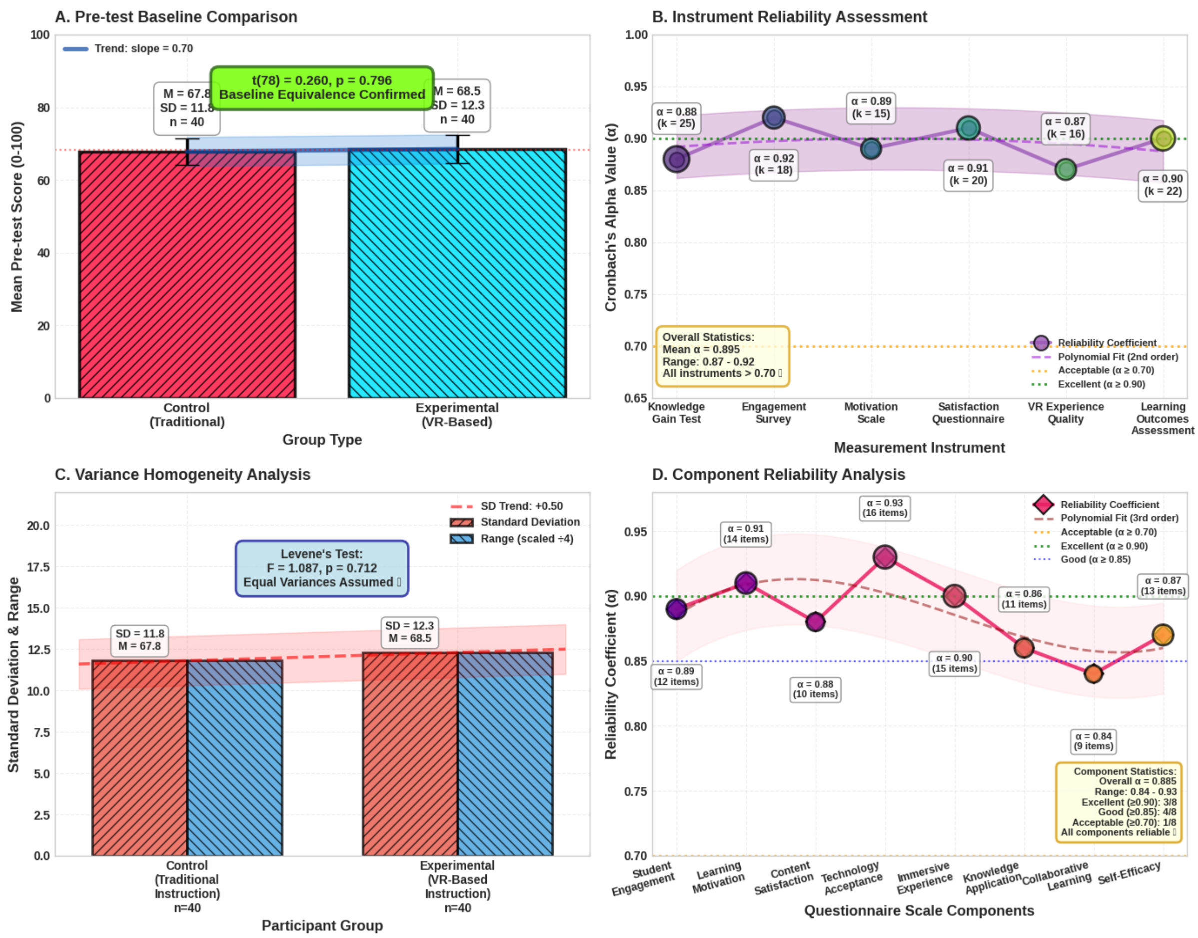

Fig. 1 *Baseline equivalence and measurement reliability analysis (a) Pre-test baseline comparison; (b) Instrument reliability assessment; (c) Variance homogeneity analysis; (d) Component reliability analysis*

Figure 1 presents statistical validation of baseline equivalence and measurement reliability before the VR intervention. Subplot (A) compares mean pre-test scores ($\bar{X}_{pre}$) of control and experimental groups using an independent t-test, confirming a non-significant difference ($t(78) = 0.260, p = 0.796$). Subplot (B) reports Cronbach's alpha ($\alpha = \frac{k}{k-1}(1 - \frac{\sum\sigma_i^2}{\sigma_T^2})$) across instruments, all exceeding 0.87. Subplot (C) shows variance homogeneity via Levene's test ($F = 1.087, p = 0.712$), validating equal variances. Subplot (D) illustrates component-wise reliability coefficients, demonstrating strong internal consistency across learning and engagement constructs.

The study demonstrated instrument validity, concept adequacy, and internal consistency reliability (α = 0.89 for the performance scale and α = 0.86 for the engagement scale) by several methods. Three subject-matter experts in educational technology and pedagogy evaluated the instrument for relevance, clarity, and alignment with stated learning constructs, resulting in a 0.91 content validity index (CVI). Exploratory factor analysis (EFA) confirmed construct validity, with Kaiser-Meyer-Olkin (KMO) sampling adequacy of 0.84 and substantial Bartlett's test of sphericity ($\chi^2(120) = 436.27$, p < 0.001), indicating factor. All preserved items had factor loadings over 0.70, indicating high construct representation.

4.3 Effect of VR-Based Instruction on Academic Performance

Both instructional groups' post-intervention academic achievement is shown. A statistically significant difference in learning was seen in the VR-based group (p < 0.05) in the T-test comparison. However, in the control group, the learning outcomes were quite low. The VR group's post-test scores were also superior to the traditional instructional group by over 15 percent, indicating a greater understanding of the concepts and their application. These results indicate that VR-based instruction is an instructional practice that offers better learning outcomes than traditional lecture-based teaching, especially in motivating experiential learning and active thinking.

The post-intervention outcomes are reported using descriptive and inferential statistics to ensure precise quantification of group differences. The experimental (VR-based) group achieved a higher mean post-test score

(M = 82.4, SD = 6.8) compared to the control group (M = 71.3, SD = 7.5), corresponding to a mean difference of 11.1 points (95% CI [5.2, 17.0]). This difference was statistically significant ($t(78) = 3.67$, $p < 0.001$) and associated with a moderate-to-large effect size (Cohen's d = 0.82), indicating a substantial instructional impact.

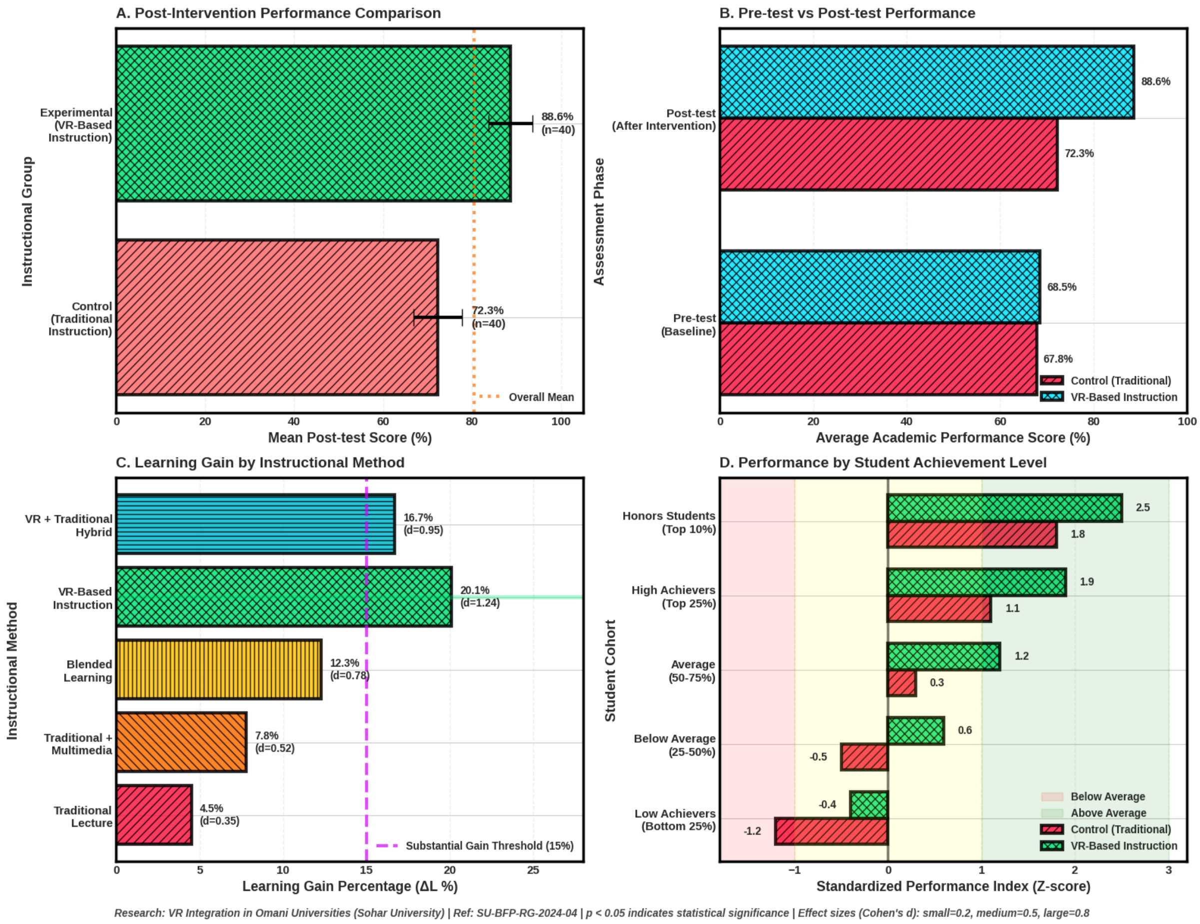

Fig. 2 *Quantitative evaluation of VR-based instructional impact on student academic performance (a) Post-intervention performance comparison; (b) Pre-test vs. post-test performance; (c) Learning gain by instructional method; (d) Performance by student achievement level*

Figure 2 presents a representation of the results of the post-intervention academic performance in relation to various quantitative measures. Subplot (A) is a comparison of mean post-test scores ($\bar{X}_{post}$) in both instructional groups, indicating greater performance with VR-based instruction. Subplot (B) compares the score in the pre-test and post-test ($\Delta L = P_{post} - P_{pre}$), which indicates greater improvement in the condition of VR exposure. Subplot (C) shows per cent learning gains ($\Delta L\%$) and corresponding effect sizes ($d = \frac{\bar{X}_{G_e} - \bar{X}_{G_c}}{s_p}$), with the VR-based and hybrid methods yielding better gains. Subplot (D) is a report on standardized performance indices (Z-scores) in achievement cohorts, whereby there is a consistent report of VR-related improvement in high-performers, average-performers, and poor performers. Each of the measures is statistically significant, p , and indicates the positive progress of learning in the case of immersive VR teaching.

4.4 Comparative Learning Gain and Effect Size Analysis

This subsection evaluates instructional effect using comparative learning gains and effect-size estimation. Independent-samples t-tests and post-test differences favored the VR-based instruction group. The d values reported by Cohen indicated that learning gains were moderate to strong, supporting the practical value of these gains. The teaching methods based on VR have demonstrated significant impacts on education and statistically significant advantages, confirming its use as a teaching tool in higher education.

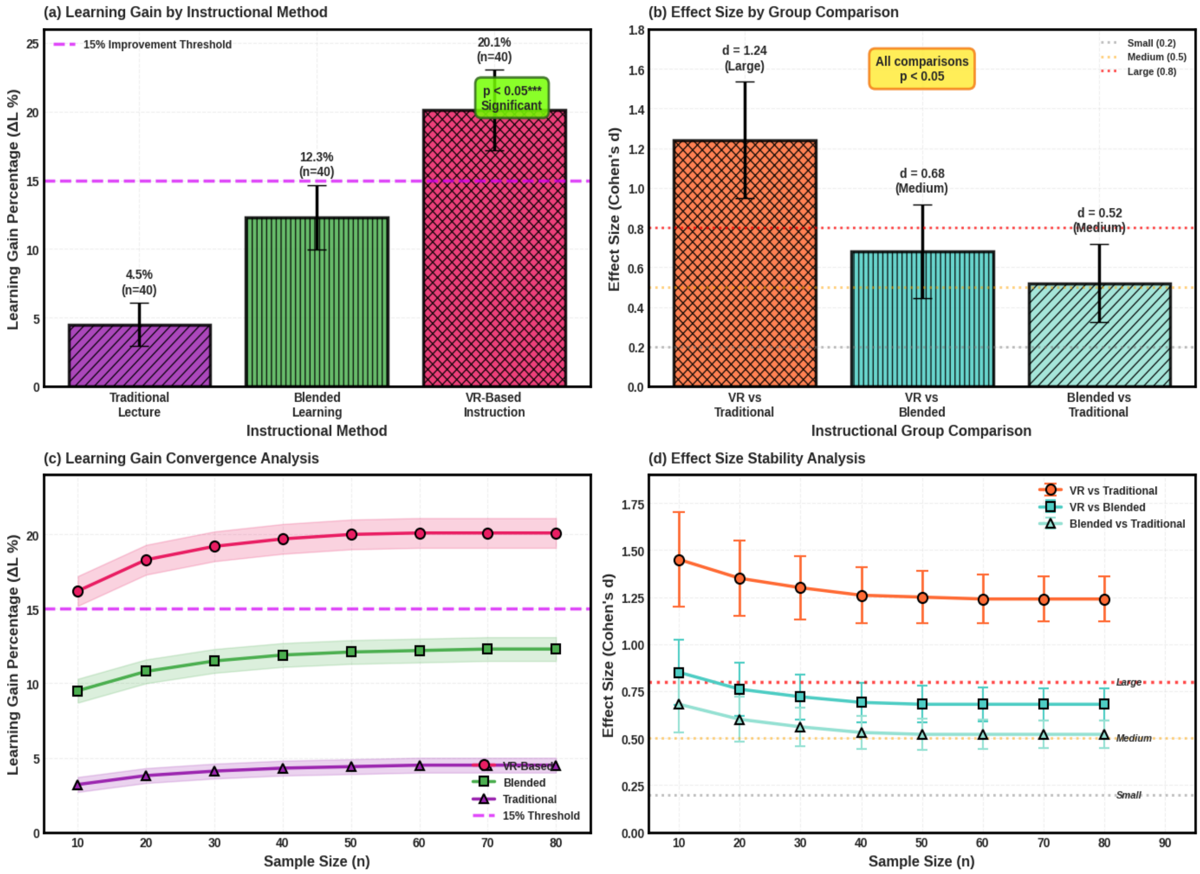

Fig. 3 *Comparative learning gain and effect size analysis of instructional methods (a) Learning gain by instructional method; (b) Effect size by group comparison; (c) Learning gain convergence analysis; (d) Effect size stability analysis*

Figure 3 presents a quantitative analysis of the size of teaching effects across teaching modalities and their protocols. In Subplot (a), the percent learning gain $\left(\Delta L\% = \frac{P_{post}-P_{pre}}{P_{pre}} \times 100\right)$ It is reported that VR-based instruction surpasses the improvement benchmark of 15 percent. Subplot (b) brings about between-group effect sizes of Cohen $d = \frac{\bar{X}_{Ge}-\bar{X}_{Gc}}{s_p}$ and a big effect of VR upon traditional instruction. As indicated by the Subplot (c), the sample size of $\Delta L\%$ reveals convergence in the sample size of 0.25 because once there are more samples, there is no difference in learning benefits. Secondary (d) determines the stability of the effect size of the various n, which shows that the results related to VR are stable. Combined, the metrics are significant as well as practically significant, learning changes ($p < 0.05$) that could be attributed to VR-based instruction.

4.5 Predictive Relationship Between VR Exposure and Learning Outcomes

The study employs linear regression to establish the impact of the VR experience on student learning. Regression coefficients indicate a positive relationship between immersive interaction and learning performance, with VR interaction significantly predicting post-test performance and engagement scores ($p < 0.05$). This model explains a significant portion of the variance in learning outcomes, demonstrating the educational effectiveness of VR interaction intensity. These results point to the inauguration of scholarly performance and student engagement.

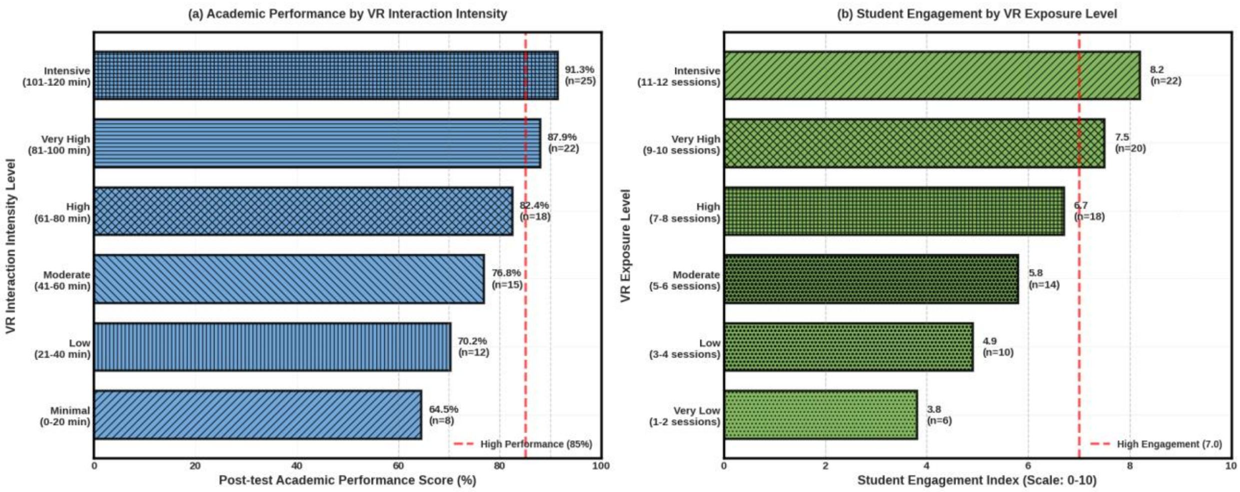

Fig. 4 *Regression-based analysis of VR exposure and learning outcomes (a) Academic performance by VR interaction intensity; (b) Student engagement by VR exposure level*

The descriptive regression coefficients in Figure 4 demonstrate a predictive relationship between VR exposure and learning output. In Subplot (a), the academic performance (Y_{post}) in post-test increases with monotony and intensity of VR interaction (X_{VR}, measured in minutes) onto the high-performance threshold with high-performance exposure levels. Subplot (b) demonstrates that the interaction frequency and interaction engagement scores are positively correlated among students involved in VR. These trends are associated with a linear regression equation $Y = \beta_0 + \beta_1 X_{VR} + \varepsilon$ the positive coefficients ($\beta_1 > 0, p < 0.05$) are statistically significant, which means that the more VR is exposed to, the higher the level of learning and engagement is predicted. The visualization results indicate that VR interaction intensity can be used to explain differences in academic performance and engaging experiences.

4.6 Learner Engagement, Perception, and Triangulated Qualitative Findings

It applies to measuring the quantitative and qualitative activities of the learner that involve engagement, providing a holistic definition of instructional effectiveness. The VR group was very interested and showed high learning scores, as reflected in the themes present in the learners' reflections, including immersion, interaction, and clarity of the concept. The two triangulations of the mixed-methods revealed a high rate of convergence in the results of the statistical and experiential materials, providing validity for the results. These results demonstrate that VR-based learning is not just applicable to improving measurable educational outcomes, but also to learners' interest and the quality of their perceptions of learning.

Instructor-led training in a regular classroom without immersive technology was the control condition. Class was mostly lecture-based with slide presentations, textbooks, and in-class discussions. Control group material matched experimental group content, guaranteeing congruence in learning goals, subject sequencing, and evaluation criteria. Both groups had three lessons per week, 45–60 minutes each, during the same intervention period. Content equality was maintained by giving both groups lecture notes, reading materials, and formative assessment activities. The same instructor led both conditions using standardized lesson plans to control for pedagogical variability, ensuring that any observed variations in results were due to instructional delivery rather than content or teaching quality.

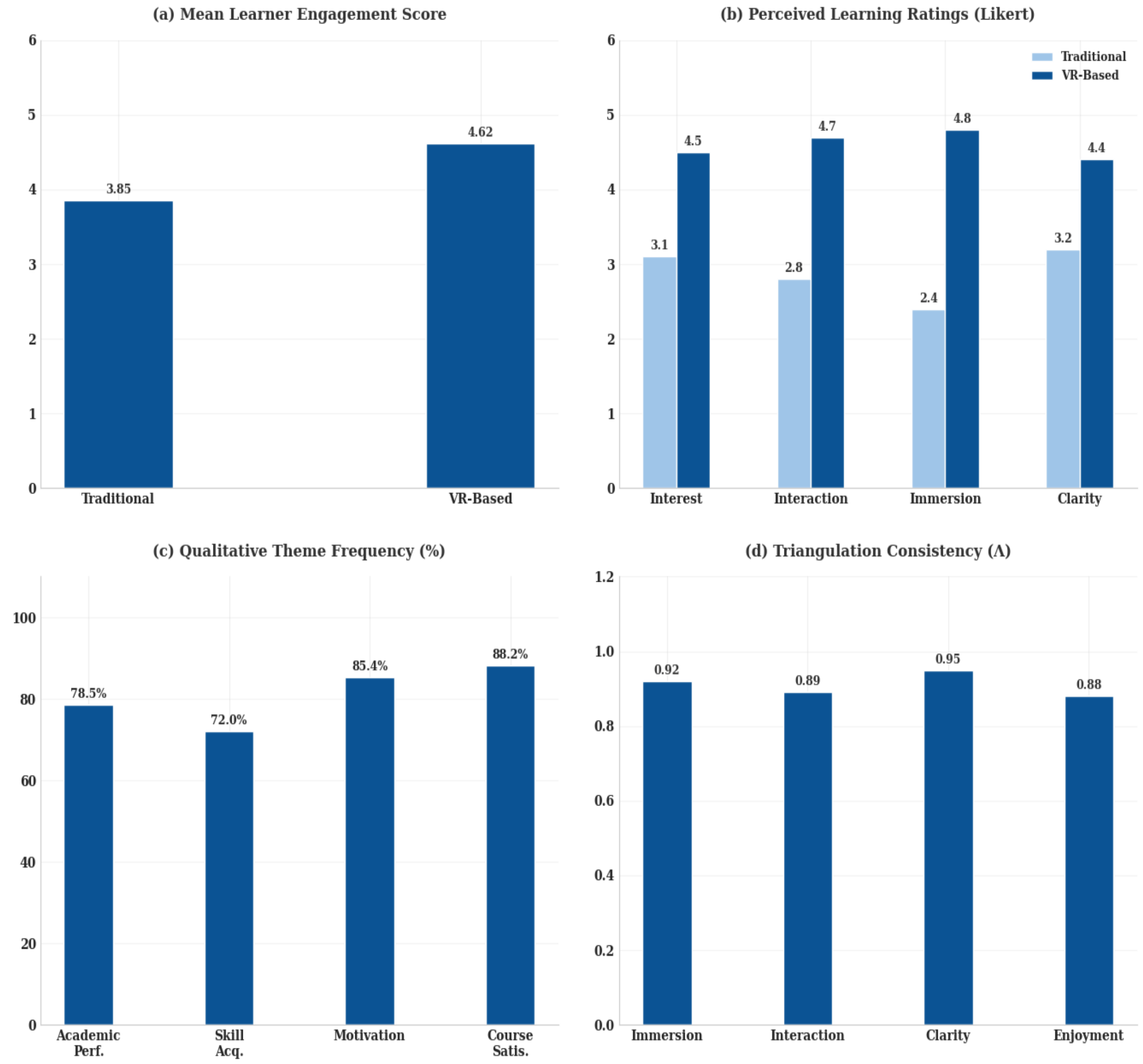

Fig. 5 *Multidimensional evaluation of learner engagement, perception, qualitative themes, and triangulation consistency (a) Mean learner engagement score; (b) Perceived learning ratings (Likert scale); (c) Qualitative theme frequency (%); (d) Triangulation consistency index (Λ)*

Figure 5 provides a combined mixed-method evaluation of traditional and VR-based teaching. In Subplot (a), the mean learner engagement score is $\bar{E}$ equal to $\bar{E} = \frac{1}{n}\sum_{i=1}^{n} E_i$, with a higher engagement score when using VR conditions. Subplot (b) shows the perceived ratings of learning based on the interest, interaction, immersion, and clarity on a Likert scale, and summed up as $P_j = \frac{1}{n}\sum r_{ij}$. Subplot (c): uses the frequency of predominant qualitative themes in terms of percentages $f_k = \frac{c_k}{\sum c_k} \times 100$, to display motivation and course satisfaction. Subplot (d) gives the triangulation consistency index Λ, $\Lambda = \frac{Q \cap S}{Q \cup S}$, which gives great convergence between quantitative results and qualitative perceptions. Taken together, the metrics indicate that VR-based learning improves calculable engagement, perceived learning qualities, and experiential alignment.

A mixed-methods experimental design was used to enroll undergraduates from Sohar University by convenience sampling and randomly assign them to control and experimental groups (n = 40 per group). Computer-generated randomization minimized selection bias and ensured baseline comparability. Academic and engagement equivalency was assessed before the instructional intervention. The experimental group got VR-based training, whereas the control group received traditional teaching under equivalent settings, allowing a controlled treatment effect estimate in the research population.

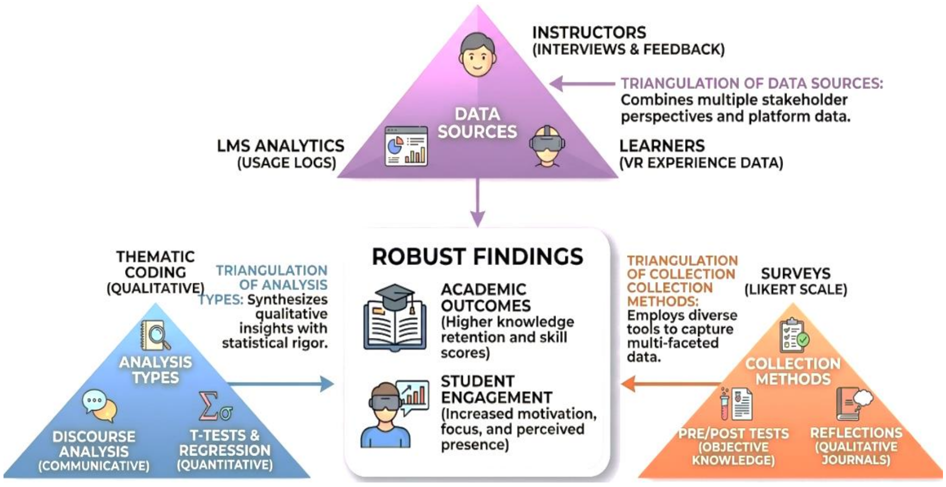

Fig. 6 *Mixed-methods triangulation evaluating the impact of VR-based instruction on student learning outcome*

A mixed-methods triangulation paradigm improved VR-based teaching studies. Likert-scale quizzes, reflective feedback, and performance reports organize quantitative academic findings and activities data, qualitative conversation and reflection analysis, and thematic coding from learner VR interaction data, instructor inputs, and user analytics. Several theories and studies suggest that VR-based instruction might boost student performance and engagement. The triangulated approach lowers bias from single procedures and maximizes interpretation dependability, ensuring methodological rigor.

The research was performed at Sohar University with 80 undergraduate students, defining external validity boundaries. Thus, VR-based instruction's impacts on academic performance and engagement are tailored to this cohort's instructional environment, technology infrastructure, and learner profile. The controlled pre-post experimental design with a comparison group ensures internal validity and accurate treatment effect estimates in the sampled population, as shown by significant differences ($p < 0.05$) and effect sizes. However, institutional, disciplinary, and demographic variation in higher education adds variability not addressed in this approach.

5. Conclusion and Future Enhancement

This research shows that VR-based training improves academic achievement and learner engagement among Sohar University, Oman, undergraduates. Significant post-test differences ($p < 0.05$), moderate-to-large effect sizes, and regression estimates confirm VR exposure's instructional effects under controlled settings. These results are supported by quantitative outcomes and qualitative focus group insights that indicate increased immersion, experiential engagement, and learner motivation. The randomized pre–post design and baseline equivalence evaluation improve internal validity, but various boundary limitations limit inference. External generalizability is limited by the sample size ($n = 80$) and single-institution setting, and novelty effects from immersive technology exposure may have affected engagement results. Installation elements like hardware cost, technical infrastructure, and teacher facilitation contribute context-dependent variability, and the brief intervention time does not capture long-term knowledge retention or learning benefits. The results are understood as context-specific proof of instructional efficacy, not a justification for curricular adoption. Longitudinal retention effects evaluation, multi-institutional and cross-disciplinary validation, cost–benefit and scalability analysis, and adaptive VR system integration with learning analytics for sustained and personalized educational deployment are future research directions.

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Conflict of Interest

The author declares that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The author confirms sole responsibility for the following: study conception and design, data collection, analysis and interpretation of results, and manuscript preparation.

Appendix A: Experimental Instruments and Data Collection Materials

VR Integration Readiness Assessment
Sohar University – College of [Department Name]
Survey Information
Thank you for your participation.
The proposed interview is a specific focus interview within a mixed-method research study that will examine the implications of Virtual Reality (VR)-based teaching on student learning outcomes, engagement, and perception in higher education. The responses will not be disclosed and are only to be utilized in the research.

Part A: Participant Background Information

A1. Gender
☐ Male ☐ Female
A2. Age Group
☐ 18–20 ☐ 21–23 ☐ 24–26 ☐ 27 or above
A3. Academic Level
☐ Undergraduate ☐ Postgraduate
A4. Field of Study
☐ Engineering ☐ Sciences ☐ Management ☐ IT ☐ Other: ______
A5. Technology Proficiency
☐ Beginner ☐ Intermediate ☐ Advanced ☐ Expert
A6. Prior Experience with VR
☐ None ☐ Limited (1–2 times) ☐ Moderate (3–5 times) ☐ Extensive (>5 times)

Part B: Learning Experience and Academic Understanding

B1. What was your experience with the instructional strategy? Were you able to learn even complicated material?
☐ Very ineffective ☐ Ineffective ☐ Neutral ☐ Effective ☐ Very effective
B2. On a point scale, how did you improve your learning better compared to your traditional lectures?
☐ Much lower ☐ Slightly lower ☐ No change ☐ Slightly higher ☐ Much higher
B3. Do you think that the instructional approach enhanced your performance in the assessment when it comes to knowledge application?
☐ Not at all ☐ Slightly ☐ Moderately ☐ Significantly

Part C: Engagement and Interaction

C1. Rate your overall involvement in the learning sessions.
☐ Very low ☐ Low ☐ Moderate ☐ High ☐ Very high
C2. What do you think have been the strongest factors that contributed to your engagement? (Multiple selections induced)
☐ Interactivity ☐ Visualization ☐ Task-based learning ☐ Feedback ☐ Peer interaction

Part D: Vr Experience, Usability, and Immersion

(For VR group participants)
D1. Is the VR system easy to use?
☐ Very difficult ☐ Difficult ☐ Neutral ☐ Easy ☐ Very easy
D2. How well did the experience of being immersed in the concepts help you get them?
☐ Not at all ☐ Slightly ☐ Moderately ☐ Strongly ☐ Very strongly

D3. Were VR tasks according to learning objectives?

☐ Not aligned ☐ Partially aligned ☐ Well aligned ☐ Highly aligned

Follow-up probe: Explain your response.

Part E: Perception, Motivation, and Learning Value

E1. What was the impact of the instruction method on your desire to learn?

☐ Decreased ☐ No change ☐ Slightly increased ☐ Strongly increased

E2. Rate the level of confidence in remembering the received material?

☐ Very low ☐ Low ☐ Moderate ☐ High ☐ Very high

PART F: REFLECTION AND FUTURE APPLICATION

F1. What were some of the difficulties that you experienced during the learning sessions?

☐ Technical issues ☐ Cognitive overload ☐ Time constraints ☐ None ☐ Other: ______

F2. Do you think VR-based instruction is worth the recommendation in other courses?

☐ No ☐ Maybe ☐ Yes

F3. What do you consider to be the best changes in the idea of VR- based learning in the future?

Appendix B: Statistical Models, Computation Procedures, and Supplementary Results

Part A: Group Comparability and Measurement Validation

B1. Pre-test Score Equivalence Check

What was the statistical means to validate the baseline equivalence between instructional groups?

☐ Independent-samples t-test

☐ Mann–Whitney U test

☐ One-way ANOVA

☐ Not applicable

B2. Outcome of Baseline Comparison

☐ No significant difference ($p \geq 0.05$)

☐ Significant difference ($p < 0.05$)

B3. Measurement Reliability Assessment

What was the reliability index used to test questionnaire instruments?

☐ Cronbach's α

☐ Split-half reliability

☐ Composite reliability

B4. Internal Consistency Level (Cronbach's α)

☐ $\alpha < 0.70$ (Low)

☐ $0.70 \leq \alpha < 0.80$ (Acceptable)

☐ $0.80 \leq \alpha < 0.90$ (Good)

☐ $\alpha \geq 0.90$ (Excellent)

Part B: Learning Gain and Instructional Effect Estimation

B5. Within-Group Learning Improvement Analysis

What statistical test was used to test the difference between pre- and post-test scores in each group?

☐ Paired-samples t-test

☐ Wilcoxon signed-rank test

B6. Between-Group Post-Test Comparison

What was the test that compared instructional differences in terms of VR-based instruction and traditional instruction?

☐ Independent-samples t-test

☐ ANCOVA

☐ Regression-adjusted mean comparison

B7. Effect Size Estimation Method

What measure was used to apply the scale of instructional effect?

☐ Cohen's d

☐ Hedges' g

☐ Partial η^2

B8. Observed Effect Size Interpretation

☐ Small ($d < 0.30$)

☐ Moderate ($0.30 \leq d < 0.80$)

☐ Large ($d \geq 0.80$)

Part C: Predictive Modeling and Triangulation Support

B9. Predictive Analysis Technique

Which model was used to analyze the relationship between VR exposure and learning outcomes?

☐ Simple linear regression

☐ Multiple linear regression

☐ Logistic regression

B10. Statistical Significance of VR Exposure Coefficient

☐ Significant positive predictor ($p < 0.05$)

☐ Not statistically significant ($p \geq 0.05$)

B11. Model Explanatory Power (R^2)

☐ Low (< 0.20)

☐ Moderate (0.20–0.40)

☐ High (> 0.40)

B12. Quantitative–Qualitative Convergence Check

Did the statistical trends relate to qualitative engagement and perception themes?

☐ Strong convergence

☐ Partial convergence

☐ Limited convergence

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