Evaluation of the Effectiveness of the Silvercoms Metaverse Based Immersive Learning Model for Satellite Communication System Education

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ABSTRACT:
Satellite communication systems education in Indonesian universities faces limitations such as expensive measuring instruments, limited access to ground stations, and a lack of virtual simulations, thus limiting students' opportunities to gain practical learning experiences in the Industry 4.0 era. This study evaluates the effectiveness of Silvercoms (Satellite Immersive Learning and Communication Model), a metaverse-based immersive learning model developed through Design Science Research Methodology, in improving learning outcomes and user experience for Telecommunication Engineering students. A quasi-experimental design with a pre-test/post-test control group was implemented at three Telkom University campuses (Bandung and Purwokerto), involving a total of 170 students divided into a control group (conventional PowerPoint-based learning) and an experimental group (Virtual Reality MetaQuest 2) using the Nusa Satelit prototype. Learning outcomes were analysed using Analysis of Covariance (ANCOVA) with pre-test scores as covariates, while user experience was evaluated using the System Usability Scale (SUS), Simulator Sickness Questionnaire (SSQ), and Learning Experience Questionnaire (LEQ). ANCOVA results confirmed a significant and positive effect of the treatment on post-test scores across all three locations (Bandung: $F(1,137)=27.47$, $p<.001$, $R^2=.834$; Purwokerto: $F(1,27)=154.29$, $p<.001$, partial $\eta^2=.851$). The prototype obtained an average SUS score of 82.8 (range 75.8–87.5), which falls into the acceptable to excellent usability category, and a low simulator sickness index (SSQ total 3.20–5.19), with disorientation as the most dominant symptom although still considered mild. All five dimensions of the LEQ were rated positive ($M>3.9$ on a scale of 1–5) across both campuses. These findings demonstrate that the Silvercoms model is an effective, easy-to-use, and physiologically tolerable alternative to conventional learning methods for satellite communication systems education, providing a validated framework that other

universities can adapt for immersive technology-based STEM learning.

Keywords: component; Immersive learning; Metaverse; Virtual reality; Satellite communications systems education; System Usability Scale; Sickness Questionnaire Simulator; Learning Experience Questionnaire; Design science research methodology.

1. Introduction

The rapid development of satellite communication systems technology and the demands of Industry 4.0 have increased the need for competency-based education (Silva-da-Nóbrega et al., 2022) and hands-on practice in the field of satellite communication systems science. However, most universities in Indonesia face persistent limitations in practical work: measurement instruments such as spectrum analyzers and ground station equipment are prohibitively expensive (Kodheli et al., 2021), access to operational ground stations is restricted due to security and regulatory concerns, and domain-specific virtual simulation resources remain limited (Yamao, 2020). As a result, students often graduate with a strong theoretical understanding but little exposure to the practical, spatial, and procedural skills required in the satellite communication systems industry.

Immersive learning within the Metaverse, facilitated by Virtual Reality (VR) (Radianti et al., 2020), Augmented Reality (AR) (Kye et al., 2021), and Mixed Reality (MR) (Peterson-Ahmad et al., 2023), has surfaced as a viable pedagogical option in engineering and STEM fields due to its capacity to replicate hazardous, costly, or physically inaccessible environments at minimal additional expense, while preserving a heightened sense of presence (Tibaldi et al., 2020), engagement, and experiential authenticity (Kyaw et al., 2019). Prior educational frameworks like the STEAM 6E teaching model have illustrated the educational merit of an inquiry driven immersive instructional cycle (Weinberger, 2022), however, they were not explicitly tailored for the technical, regulatory, and curricular environments of satellite communications systems education (Atta et al., 2022), nor have they been substantiated through a synthesis of usability, health, and pedagogical assessments across various institutions

To address this gap, using Design Science Research Methodology (DSRM) was implemented to identify required features, design and develop, and empirically test a metaverse based immersive learning model for satellite communication systems education (Peffers et al., 2007). In Figure 1 the resulting artifact, Silvercoms model (Satellite Immersive Learning and Communication Model) (Akbar, K. et al., 2024) integrates the 6E Instructional Model (Engage, Explore, Explain, Engineer, Enrich, Evaluate) (C. L. Lin & Chiang, 2019), the Motivated Strategies for Learning Questionnaire (MSLQ)(Şen et al., 2015) as a reinforcement of motivational and metacognitive aspects, a seven-layer metaverse infrastructure (7 layers), and a People Process Technology implementation framework. This model is realized as a functional VR prototype named Nusa Satelit, built using Unity and running on a Meta Quest 2 device.

Although the broader dissertation research addresses feature identification (RQ1) and model building (RQ2), this article specifically focuses on the empirical evaluation stage of the research and answers the following research question: How effective is the Silvercoms model in improving learning outcomes and user experience, as measured through the System Usability Scale (SUS), Simulator Sickness Questionnaire (SSQ), and Learning Experience Questionnaire (LEQ)?

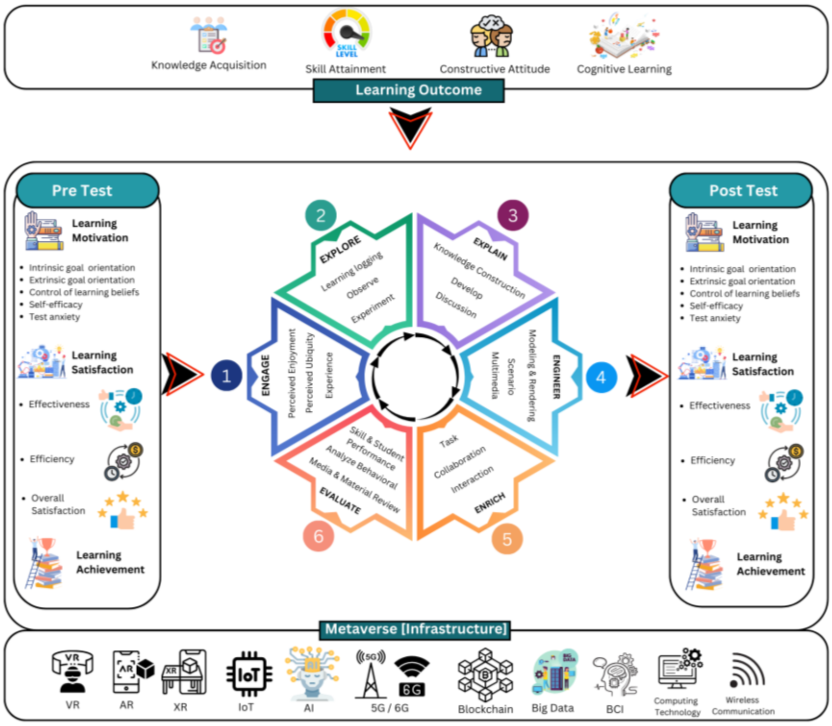

Figure 1. Silvercoms Model

This article contributes to the literature in three ways. First, it provides multi-site (two campuses) quasi-experimental evidence on the effectiveness of a metaverse-based immersive learning model in the previously under-researched domain of satellite communication systems education. Second, it demonstrates a replicable evaluation protocol by triangulating an analysis of learning outcomes (ANCOVA) with usability (SUS), physiological tolerance (SSQ), and multidimensional learning experience (LEQ) instruments. Finally, it offers practical design and implementation guidance for institutions considering VR based practicum alternatives in resource-constrained environments.

2. Literature Review

2.2. Metaverse and Immersive Learning in Higher Education

The Metaverse encompasses a set of interrelated technologies including VR, AR, MR, real-time 3D rendering, avatars, and persistent virtual worlds (Park & Kim, 2022) that collectively enable synchronous, embodied, and spatially rich learning experiences (Kurniawan et al., 2019). In immersive learning environments, learners gain a heightened sense of presence and agency (Park & Kim, 2022), which are difficult to replicate in traditional lecture- or slide-based learning, especially for materials that are spatial, procedural, or dangerous to practice on physical devices, such as satellite launches, orbital mechanics, and ground station operations.

2.3. Instructional Design: The 6E Model and MSLQ

The 6E Instructional Model extends the commonly used 5E cycle by adding an "Engineer" stage, structuring learning into six stages: Engage, Explore, Explain, Engineer, Enrich, and Evaluate, which guide learners from initial curiosity to structured explanations, applied engineering practices, enrichment, and formative evaluation (Y. H. Lin et al., 2023) 6E STEAM instructional model demonstrates the application of this conceptual cycle to immersive STEM learning and serves as one of the primary conceptual references in the design of Silvercoms. To strengthen the motivational and metacognitive dimensions of learning (de Araujo et al., 2023), the Motivated Strategies for Learning Questionnaire (MSLQ) instrument is embedded in the pre-test/post-test evaluation cycle to capture learners' self-regulation and learning strategies in addition to cognitive outcomes (Hilpert et al., 2013).

2.4. Evaluation Instruments: SUS, SSQ, and LEQ

The System Usability Scale (SUS), a ten-item Likert-based instrument developed by Brooke (1996), remains the most widely used "quick and simple" measure of usability; scores are converted to a 0–100 scale, with scores above 68 generally considered above average (Bangor et al., 2009) . The Simulator Sickness Questionnaire (SSQ) breaks down VR-induced discomfort into three subscales: Oculomotor, Nausea, and Disorientation and has become the de facto standard for assessing physiological tolerance of head-mounted display experiences (Gonçalves et al., 2024). The Learning Experience Questionnaire (LEQ) used in this study is a multidimensional instrument encompassing five dimensions: Engagement and Immersion, Content and Pedagogy, Interactivity and Collaboration, Technical Performance, and Learning Outcomes that collectively capture the cognitive, affective, and social qualities of learners' learning experiences in immersive environments (Gustav et al., 2022).

2.5. Design Science Research Methodology

Design Science Research Methodology (DSRM) (Peffers et al., 2007), provides a structured and iterative process for developing and evaluating information system artifacts: problem identification and motivation, solution goal setting, design and development, demonstration, evaluation, and communication (vom Brocke et al., 2020). DSRM was chosen for this research because its intended contribution is not only empirical findings, but also validated and reusable prototype models and artifacts (Akoka et al., 2023) Silvercoms and Nusa Satelit that can be adopted or adapted by other institutions.

2.6. Research Gaps

Although metaverse-based immersive learning has been explored in various engineering and health science domains (Naderi & Shojaei, 2023), multi-site empirical evaluations that simultaneously assess the effectiveness of learning outcomes (Mang et al., 2023), usability (Bangor et al., 2009), physiological tolerance, and multidimensional learning experiences are still rare (Akour et al., 2022), especially in the satellite communication systems education domain, which is characterized by high equipment costs (Ahmad et al., 2023), limited physical access, and stringent regulatory constraints (Chandramouli et al., 2023). This study fills this gap through a three instrument quasi-experimental evaluation (Ronaghi, 2023) of Silvercoms reported below.

3. Research Methodology

3.1. Research Design

Table 1. Student Stratification

Group	Range GPA	# Students Tel U Bandung	# Students Tel U Purwokerto
Experimental Group	3.2 s.d 4.00	33 Students	8 Students
	2.5 s.d 3.19	37 Students	7 Students
Total Students in the Experimental Group		**70 Students**	**15 Students**
Control Group	3.2 s.d 4.00	33 Students	8 Students
	2.5 s.d 3.19	37 Students	7 Students
Total Students in the Control Group		**70 Students**	**15 Students**
Grand Total Students		**140 Students**	**30 Students**

This article reports on the evaluation phase of a broader DSRM based research program. A quasi-experimental design with pre-test/post-test non-equivalent control groups was used because full randomization was not possible under real-world classroom conditions. Participants were divided into two groups: a control group receiving conventional instruction using static PowerPoint (PPTX) presentations, and an experimental group receiving immersive instruction using the Nusa Satelit VR prototype on the MetaQuest 2 device. In Tabel 1 to minimize selection bias, students were stratified based on their Grade Point Average (GPA) between 3.20–4.00 and 2.50–3.19 before being allocated into the two groups, ensuring equivalence of initial academic ability.

3.2. Silvercoms Model and Nusa Satelit Prototype

Silvercoms (Satellite Immersive Learning and Communication Model) integrates four dimensions of evidence-based features identified through a systematic literature review (SLR) and focus group discussions (FGD) with experts for the elements of Technology Infrastructure, Immersive Design, Interaction, and Learning Outcome which are operationalized through 20 detailed elements (Akbar, K. et al., 2024). Pedagogically, this model follows the 6E Instructional cycle and is reinforced by the MSLQ instrument at the pre-test and post-test stages. This model is implemented as Nusa Satelit, a Unity-based VR application that has a lobby area, an interactive 3D simulation of a satellite launch, and a central area for collaborative activities and assessments, which is run on a Meta Quest 2 device.

3.3. Research Location and Participants

Using purposive sampling, two Telkom University campuses Bandung and Purwokerto were selected based on their suitability of curriculum, technological infrastructure, and student population characteristics to support VR-based practicum research. Data collection was conducted over approximately three months. The combined sample size was 182 undergraduate Telecommunication Engineering students: 140 in Bandung (95 males, 45 females), and 30 in Purwokerto. Table 2 summarizes participant characteristics and instrument reliability across the three locations.

Table 2. Participant Demographics and Instrument Reliability by Research Location

Characteristics	Bandung	Purwokerto	Combined
# samples (N)	140	30	182
Gender (P/W)	95 / 45	12/18	107/53
Cronbach's alpha (12 item)	.837	.812	All > .70
Pre-test normality	Abnormal (p<.05)	Normal (Shapiro–Wilk)	Mixed
Inferential tests used	Mann–Whitney U / Wilcoxon	Paired-samples t-test	+ANCOVA (All Location)

3.4. Instrument

Learning outcomes were measured through pre-test/post-test scores paired with satellite communication system materials. Usability was assessed with the ten-item SUS (score = mean item score × 2.5, resulting in a scale of 0–100). Physiological tolerance was assessed with the ten-item SSQ, scored on the Oculomotor, Nausea, and Disorientation subscales and converted to a weighted total score following the official scoring procedure of Kennedy et al. (1993), interpreted using the categories: <5 no symptoms, 5–10 very mild, 10–15 mild, 15–20 moderate, >20 severe. The Learning Experience Questionnaire (LEQ) uses a five-point Likert scale (1 = strongly disagree to 5 = strongly agree) on 20 items arranged in five dimensions, interpreted using the following categories: 1–1.8 very low, 1.81–2.6 low, 2.61–3.4 medium, 3.41–4.2 high, 4.21–5 very high. All instruments were content-validated by academics and industry practitioners through FGDs prior to data collection

3.5. Statistical Analysis Procedure

In Figure 2, data were analyzed using SPSS. Descriptive statistics (frequency, percentage, mean, median, mode, standard deviation, minimum, and maximum) were used to describe the respondent profile and instrument scores. Normality was assessed using the Kolmogorov–Smirnov and Shapiro–Wilk tests ($\alpha = .05$); non-normally distributed data were analyzed using the Mann–Whitney U test (initial equality between groups) and the Wilcoxon signed-rank test (pre–post changes within groups), while normally distributed data were analyzed using the paired-samples t-test. Instrument validity was assessed using the Pearson product-moment correlation (item-total correlation, $p < .05$), and internal consistency was assessed using Cronbach's alpha ($\alpha > .70$ indicates good reliability). The primary effectiveness test was Analysis of Covariance (ANCOVA), with post-test scores as the dependent variable, learning method (control vs. experimental) as the independent variable, and pre-test scores as the covariate, run separately for each campus given the differences in sample size and distribution characteristics across sites.

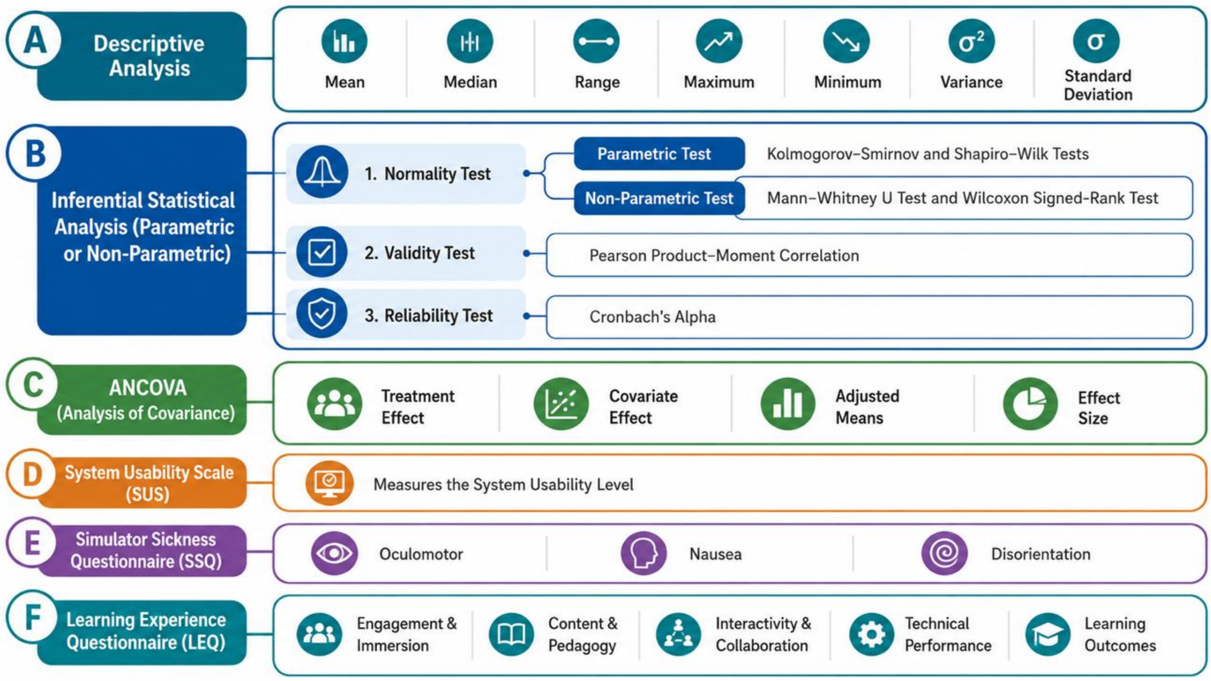

Figure 2. Statistical Analysis Procedure

4. Results

4.1. Initial Equivalence And Instrument Quality

Before treatment, a mann-whitney u test in bandung confirmed no significant difference in pre-test scores between the control and experimental groups ($u = 2344.50$, $z = -0.44$, $p = 0.657$), indicating that the stratified allocation based on GPA successfully produced academically equivalent groups. A similar initial balance was achieved in purwokerto through the same stratification procedure. In both locations, pearson product-moment correlations confirmed that most instrument items were positively and significantly correlated with the total score ($p<0.05$ or $p<0.01$), and cronbach's alpha exceeded the threshold of 0.70 in each location (bandung α=0.837; purwokerto α=0.812; 12 items each), confirming sufficient instrument validity and reliability for further analysis.

4.2. Learning Outcomes

Descriptively, the average score increased in each location after treatment, with consistently greater increases in the experimental group. In bandung, the average score of the experimental group increased from 39.61 to 57.77, compared to 41.03 to 47.61 in the control group. In purwokerto, the experimental group achieved an average increase of 23.80 points, compared to 3.87 points in the control group. An ancova test, controlling for pre-test scores as a covariate, confirmed that these differences were statistically significant across all three locations (table 3).

Table 3. Ancova Results For Post-Test Scores By Study Location (Covariate: Pre-Test)

Location	N	Df	F (Metode)	Sig.	R^2 (Adj. R^2)	Effect Size
Bandung	140	1, 137	27,472	<,001	,834 (,831)	Big
Purwokerto	30	1, 27	154,289	<,001	,882 (,874)	Very Large (Partial H^2=,851)

4.3. Usability (System Usability Scale)

The Nusa Satelit prototype achieved a SUS score of 75.8 in Bandung and 87.5 in Purwokerto, resulting in a combined average of 82.8 in the "excellent" category on the conventional SUS adjective scale and well above the 68-point threshold for above-average usability in each location (Table 4).

Table 4. System Usability Scale (Sus) Results By Research Location

Location	N	Average Score Sus	Predicate	Acceptability
Bandung	70	75,8	Good	Acceptable
Purwokerto	15	87,5	Excellent	Acceptable
Average	**91**	**82,8**	**Excellent**	**Acceptable**

4.4. Physiological Tolerance (Simulator Sickness Questionnaire)

The total SSQ score was low across all three sites (3.20 in Bandung and 5.19 in Purwokerto), which falls within the "no symptoms" to "very mild" range on the standard interpretation scale. At each site, the Disorientation subscale was the most prominent symptom dimension, followed by Nausea, while Oculomotor symptoms were consistently the mildest (Table 5). This pattern suggests that residual discomfort is primarily caused by perceived mismatches between head movements and visual feedback, rather than by eyestrain or typical nausea symptoms.

Table 5. Simulator Sickness Questionnaire (SSQ) Subscale and Total Scores by Study

Location	Oculomotor	Nausea	Disorientation	Total SSQ
Bandung	6,39	7,31	13,32	3,20 (No Symptoms)
Purwokerto	10,99	12,30	19,49	5,19 (Very Light)

4.5. Learning Experience Questionnaire (LEQ)

All five LEQ dimensions were rated positively at each location (M > 3.9 on a scale of 1–5). In Bandung, Content and Pedagogy was rated highest (M=4.237) and Learning Outcomes the lowest (M=3.952). In Purwokerto, Interactivity and Collaboration was rated highest (M=4.533), while Content and Pedagogy and Technical Performance were tied for the lowest (M=4.453). Overall, Purwokerto recorded the highest aggregate LEQ score, followed by Bandung, in line with the same order in the SUS results (Table 6).

Table 6. Learning Experience Questionnaire (LEQ)

Location	Highest Dimension	Mean	Lowest Dimension	Mean
Bandung	Content & Pedagogy	4,237	Learning Outcomes	3,952
Purwokerto	Interactivity & Collaboration	4,533	Content & Pedagogy / Tech. Performance	4,453

4.6. User Satisfaction and Previous VR Experience

Post-session subjective ratings were generally positive. In Tabel 7 Feelings of Using Virtual Reality on the Bandung Campus (n=70), 28 respondents reported being "very satisfied" and 29 "satisfied," with 7 "neutral," 2 "dissatisfied," and 4 "very dissatisfied."

Table 7. Feelings of Using Virtual Reality on the Bandung Campus

Question	Category	# Answers	Interpretation
Your current feelings about learning using the metaverse	5	28	Very Satisfied
	4	29	Satisfied
	3	7	Neutral
	2	2	Dissatisfied
	1	4	Very Dissatisfied
	Total	**70**	

In Tabel 8 Feelings of Using Virtual Reality on the Purwokerto Campus (n=15), all respondents gave positive ratings (11 "very satisfied," 4 "satisfied"). Previous VR experience varied across locations: in Bandung, 34 of the 70 respondents had never used VR before the study, while in Purwokerto the majority of respondents had at least some prior VR experience, suggesting that high usability and satisfaction do not depend on extensive prior familiarity with the technology.

Table 8. Feelings of Using Virtual Reality on the Purwokerto Campus

Question	Category	# Answers	Interpretation
Your current feelings about learning using the metaverse	5	11	Very Satisfied
	4	4	Satisfied
	3	0	Neutral
	2	0	Dissatisfied
	1	0	Very Dissatisfied
	Total	**15**	

5. Discussion

This study aimed to determine the effectiveness of the Silvercoms model in improving learning outcomes and user experience, as measured by the SUS, SSQ, and LEQ. Converging evidence from three independent campus sites, each differing in sample size, demographic composition, and even the type of parametric or non-parametric statistical test appropriate to the data distribution, provides a strong answer: the model produces statistically significant and practically meaningful improvements in learning outcomes (all ANCOVAs $p<0.05$, with large to very large effect sizes), is rated as having very high usability (mean SUS = 82.8, "excellent"), and induces only low levels of simulator sickness (SSQ 3.20–5.19), while learners report a consistently positive multidimensional learning experience (all LEQ dimensions $M>3.9$).

The consistent significance of the ANCOVA across the three sites, despite the relatively small sample size in Jakarta ($n=12$) and therefore less statistical power than in Bandung ($n=140$), strengthens the belief that the observed effects can be attributed to the immersive learning intervention, rather than to the unique characteristics of each site. This cross-site consistency also addresses a common criticism of single-site immersive learning research: that positive effects may be influenced by novelty effects unique to a single class or instructor. Stratification of participants by GPA prior to random allocation, combined with confirmed baseline equivalence (Mann–Whitney U, $p=0.657$ in Bandung), further supports the internal validity of this comparative design.

The usability results (SUS 75.8–87.5) compare favorably with the widely cited 68-point threshold for above-average usability, and the highest value in this range (87.5 in Purwokerto) approaches the upper limit of the scale. Combined with the low SSQ scores, these results suggest that the metaverse-based prototype achieves a combination rarely found in VR-based learning research: high perceived usability without significant physical comfort costs. The consistent dominance of the Disorientation subscale over Oculomotor and Nausea symptoms across all three sites is a noteworthy and actionable finding: it points specifically to head tracking latency and visual motion mismatch as the primary sources of residual discomfort, rather than visual fatigue or classic motion sickness. This suggests that further optimization efforts should prioritize frame rate stability, tracking precision, and locomotion design (e.g., teleportation versus continuous movement) over changes to visual fidelity or session duration alone.

The LEQ results show a consistent ordering across Purwokerto > Bandung locations, which aligns with the SUS ordering, suggesting that perceived system usability and perceived quality of the learning experience are closely related in this context, likely because a smoother and more responsive VR experience reduces cognitive load that would otherwise be diverted from the learning material. Results at the dimension level also carry design implications: Bandung's relatively lower Learning Outcomes scores, despite strong Content and Pedagogy assessments, suggest that additional formative feedback or knowledge transfer support may be needed for larger cohorts, while uniformly high Interactivity and Collaboration and Engagement and Immersion assessments across locations validate the model's core design premise that direct manipulation of virtual satellite components and a strong sense of presence are key drivers of the model's pedagogical value.

Compared with general-purpose immersive STEM instructional models such as STEAM-6E (Lin et al., 2023), Silvercoms extends the underlying 6E cycle with domain-specific technology infrastructure and interaction design requirements drawn from a systematic literature review and focus group discussions with experts, and to the authors' knowledge, it is one of the first in this field to be validated using a combined ANCOVA, SUS, SSQ, LEQ evaluation protocol across multiple institutions, rather than a single classroom. This triangulated evaluation strategy addresses calls in the immersive learning literature for evaluations that not only measure learning outcomes but also capture usability and physiological tolerance, both of which determine whether pedagogically sound interventions are sustainable in real-world institutional settings.

6. Research Limitations

Several limitations should be considered when interpreting these findings. First, the evaluation period was limited to only about three months, making it impossible to assess long term knowledge retention or motivational sustainability. Second, testing was conducted using a single VR hardware platform (MetaQuest 2), results may not be generalizable to other headsets with different tracking fidelity, field of view, or ergonomics. Third, external variables such as students' intrinsic motivation and early digital literacy were not fully controlled and may contribute to residual variance in learning outcomes and user experience ratings. Finally, because the quasi experimental design did not employ full randomization, potential residual confounding from unmeasured variables cannot be completely ruled out despite GPA stratification procedures.

7. Conclusion

This study evaluated the effectiveness of Silvercoms, a metaverse-based immersive learning model for satellite communications systems education, at three college campuses using a three-instrument quasi-experimental evaluation protocol. The model produced statistically significant learning outcomes at each site (ANCOVA $p<0.05$, large to very large effect sizes), achieved excellent average usability scores (SUS = 82.8), elicited only low levels of simulator sickness (SSQ 3.20–5.19), and was associated with a consistently positive multidimensional learning experience (LEQ $M>3.9$ across all dimensions). Overall, these results confirm that the Silvercoms model is an effective and well-tolerated alternative to conventional learning for satellite communications systems education and offers a validated and replicable framework that integrates the 6E Instructional Model, the MSLQ, the seven-layer metaverse infrastructure, and the People Process Technology implementation framework for institutions seeking to adopt immersive learning in resource-constrained STEM contexts.

Future research should expand this evaluation with larger, more balanced samples across sites, longer observation periods to assess knowledge retention, cross-platform comparisons of hardware types, and controlled investigations into specific technical factors (e.g., tracking latency, locomotion method) that contribute to residual disorientation symptoms. Institutions considering adopting this model are advised to pursue a phased, hybrid implementation strategy, combined with VR infrastructure investment, faculty training, and curriculum integration, in line with the recommendations emerging from this study.

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CONFLICT OF INTEREST

The authors certify that there is no conflict of interest with any financial organization regarding the material discussed in the manuscript.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization	I : **I**nvestigation	Vi : **Vi**sualization
M : **M**ethodology	R : **R**esources	Su : **Su**pervision
So : **So**ftware	D : **D**ata Curation	P : **P**roject administration
Va : **Va**lidation	O : Writing - **O**riginal Draft	Fu : **Fu**nding acquisition
Fo : **Fo**rmal analysis	E : Writing - Review & **E**diting	

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