OmniaScience

Journal of Technology and Science Education

JOTSE, 2026 – 16(1): 262-274 – Online ISSN: 2013-6374 – Print ISSN: 2014-5349

https://doi.org/10.3926/jotse.3684

AN EXPERIMENTAL COMPARATIVE STUDY OF VIRTUAL REALITY AND AUGMENTED REALITY FOR TEACHING SOLAR SYSTEM IN PRIMARY EDUCATION

Potsirin Limpinan[1*], Weerapat Pichetphon[1], Thanet Yuensook[1], Thada Jantakoon[2]

[1]Faculty of Information Technology, Rajabhat Mahasarakham University (Thailand)

[2]Faculty of Science and Technology, Rajabhat Mahasarakham University (Thailand)

[*]*Corresponding author: potsirin.li@rmu.ac.th*
669220650101@rmu.ac.th, thanet.y@rmu.ac.th, thada.phd@gmail.com

Received July 2025
Accepted February 2026

Abstract

This study examined the comparative effectiveness of Virtual Reality (VR) and Augmented Reality (AR) technologies in enhancing primary students' understanding of solar system concepts. A quasi-experimental design was employed involving 60 second-grade students assigned to three instructional groups: VR-based learning, AR-based learning, and traditional instruction. Learning achievement was measured using pre-test and post-test assessments, while knowledge retention and student satisfaction were evaluated following the intervention. To account for baseline differences in prior knowledge, Analysis of Covariance (ANCOVA) was conducted to compare post-test learning achievement across groups using pre-test scores as a covariate. The ANCOVA results indicated a statistically significant effect of instructional method on post-test performance ($F(2, 56) = 72.15$, $p < .001$, $\eta^2 = 0.72$). Bonferroni-adjusted pairwise comparisons based on adjusted post-test means revealed that both the VR ($M_{adj} = 16.78$) and AR ($M_{adj} = 15.33$) groups achieved significantly higher learning outcomes than the control group ($M_{adj} = 12.41$). Furthermore, the VR group demonstrated significantly higher adjusted post-test achievement than the AR group after controlling baseline differences in prior knowledge ($p = .004$). Retention analysis indicated that both experimental groups maintained higher knowledge retention rates after a two-week interval compared to the control group. These findings suggest that immersive learning environments, particularly VR-based instruction, can significantly improve learning achievement and retention in primary science education.

Keywords – Virtual reality, Augmented reality, Solar system, Immersive learning, Primary education.

To cite this article:

Limpinan, P., Pichetphon, W., Yuensook, T., & Jantakoon, T. (2026). An experimental comparative study of virtual reality and augmented reality for teaching solar system in primary education. *Journal of Technology and Science Education, 16*(1), 262–274. https://doi.org/10.3926/jotse.3684

----

1. Introduction

In current science education, virtual reality (VR) technologies' including those within the realm of augmented reality (AR), are growing, allowing presence phenomena, which were difficult to understand broadly on a cognitive level, to become testable and perceptible. The solar system, with its numerous complicated spatial aspects at large scales, is known to pose significant cognitive difficulties for young students in primary school (Plummer, 2014; Lelliott & Rollnick, 2010). Research has consistently shown that young learners struggle to comprehend astronomical concepts due to their abstract nature and the need for three-dimensional spatial reasoning (Vosniadou & Brewer, 1992). This barrier emphasizes the urgent call for novel instructional strategies that promote the development of deeper understanding in astronomy. To address these challenges, incorporating immersive technologies like VR and AR can facilitate experiential learning, enabling students to visualize and interact with astronomical phenomena more effectively (Carneiro et al., 2024). Previous studies have demonstrated that AR can significantly enhance students' understanding of complex astronomical concepts by allowing them to manipulate and visualize celestial bodies in a more intuitive way (Chiang et al., 2019; Fleck & Simon, 2013; Zhang et al., 2014). This innovative approach not only improves cognitive learning achievement but also fosters essential skills such as critical thinking and problem-solving in science education. By engaging students in interactive environments, AR can significantly enhance their motivation and understanding of complex spatial relationships in the solar system

Among emerging technological interventions, virtual reality (VR) and augmented reality (AR) have shown potential in improving learner engagement, understanding, and retention in K–12 science education. VR allows for total immersion in virtual worlds, while AR superimposes virtual information onto the real world and provides situated learning and visual scaffolding experiences. Research also suggests that these kinds of immersive experiences are key to building accurate mental models and spatial reasoning integral to comprehension about how planets move and relate to each other. Yet, despite these advancements, there are few comparative studies investigating the pedagogical efficacy of VR when compared to AR. The existing studies mostly study single-mode, and they are based on secondary or higher education. In addition, among the field of elementary science classrooms, few experiment designs measuring learning performance, knowledge retention, and user perceptions across both technologies exist. To the best of our knowledge, there has been a lack of specific rigorous review comparing VR and AR solar system interventions. Guided by educationally aligned practices and Journal of Science Education and Technology-driven frameworks, two customized VR applications, VR Solar Jelly and AR Solar Jelly, were developed. Using a randomized, experimental design with second graders, we evaluate three main outcomes: (1) learning performance, (2) knowledge retention, and (3) user satisfaction.

Therefore, this study adds to the literature base by answering an important question related to educational technology: which immersive modality leads to a higher level of learning performance? Which platforms produce the greatest level of long-term knowledge retention between VR and AR? And what do they mean to young learners in terms of access and play. These findings have major implications for project managers, educators, and policymakers who strive to incorporate immersion tools in science-based education.

2. Research Objectives

This study aims to investigate the comparative effectiveness of Virtual Reality (VR) and Augmented Reality (AR) technologies in facilitating science learning among primary school students, specifically in the domain of astronomy education. The specific research objectives are as follows

1. To compare the learning achievement of primary school students who receive instruction through VR, AR, and traditional teaching methods in the context of solar system education.

2. To evaluate the retention of scientific knowledge related to solar system concepts among students in VR-based, AR-based, and traditional instruction groups over a two-week period following the intervention.

3. To assess student satisfaction with VR and AR learning environments across key dimensions, including perceived media interest, ease of use, interactivity, and engagement.

4. To explore the pedagogical implications of implementing immersive learning technologies (VR and AR) in primary science education, based on empirical evidence collected through experimental methods.

3. Literature Review

3.1. Virtual Reality and Augmented Reality in Primary Education

Virtual Reality (VR) and Augmented Reality (AR) have emerged as transformative technologies in primary education, offering innovative approaches to enhance learning experiences through immersive and interactive environments. These technologies have demonstrated significant potential across various subjects, particularly in science, mathematics, and STEAM education, where they facilitate improved learning outcomes through semi-immersive experiences (Zuo et al., 2025). For instance, a systematic review by Ercoşkun et al. (2024) found that AR applications in primary education consistently improved student engagement and conceptual understanding across multiple disciplines. AR technology has proven especially effective in supporting inquiry-based teaching methods and bridging traditional and digital literacy gaps (Gunčaga et al., 2024), while simultaneously enhancing scientific literacy and student engagement. Research indicates that both VR and AR significantly increase student interest and material retention (Demitriadou et al., 2020), while fostering the development of essential digital, technical, and artistic skills that prepare students for an increasingly technology-driven world (Gunčaga et al., 2024).

Despite their educational benefits, the implementation of VR and AR technologies in primary education faces several significant challenges that require careful consideration. Primary concerns include substantial hardware and software investment requirements, alongside the necessity for comprehensive educator training (Demitriadou et al., 2020). The complexity of designing pedagogically sound learning tasks that effectively utilize these technologies while aligning with curriculum goals presents another notable challenge (Zuo et al., 2025). Additionally, accessibility issues and high costs can impede widespread adoption in educational settings (Mahmoudi-Dehaki & Nasr-Esfahani, 2024). However, these challenges underscore the importance of continued research and collaborative efforts to optimize VR and AR applications for educational environments, ensuring their potential benefits can be fully realized while addressing implementation barriers effectively.

3.2. Immersive Learning Experiences

Immersive learning experiences through Virtual Reality (VR) and Augmented Reality (AR) are revolutionizing educational landscapes by providing interactive and experiential learning opportunities. These technologies enable students to explore complex subjects through simulations and virtual environments, significantly enhancing engagement and understanding. Research indicates that VR applications particularly excel in fostering the development of interpersonal skills and critical competencies in higher education (Cabrera-Duffaut et al., 2024; Kapralos, 2024), while universally designed VR applications improve accessibility and user satisfaction across diverse audiences (Szentirmai, 2024).

The implementation of immersive technologies, however, faces several significant challenges that require careful consideration. Primary barriers include the high costs of hardware and software, technological complexity, and the persistent digital divide that limits equal access to these educational tools. Additionally, the need for comprehensive teacher training to effectively utilize these technologies presents another crucial challenge in their integration into educational settings.

Looking towards the future, educators and policymakers are encouraged to invest in immersive technologies while providing adequate training to harness their full potential. The development of cost-effective, cross-platform VR solutions and VR-specific accessibility guidelines is essential for broader educational application (Szentirmai, 2024). Furthermore, innovative pedagogical models, such as the immersive flipped classroom, show promise in enhancing student engagement and learning outcomes (Alizadeh, 2024), suggesting that immersive learning will play an increasingly important role in shaping the future of education.

3.3. Augmented and Virtual Reality in Natural Science Learning

Augmented Reality (AR) and Virtual Reality (VR) technologies are increasingly being integrated into natural science education, offering immersive and interactive experiences that enhance learning outcomes. Studies have demonstrated significant improvements in student understanding of complex scientific concepts, with some research showing up to 80% improvement in post-test scores when using these technologies for teaching subjects like human anatomy (Poveda-Mora et al., 2024). This enhanced learning experience extends to higher education, where immersive technologies facilitate deeper understanding and retention of complex material (Tene et al., 2024), while simultaneously increasing student motivation and engagement in the learning process (Subran & Mahmud, 2024).

The implementation of AR and VR in educational settings has shown particular promise in supporting collaborative learning environments. Research indicates that students working together in shared virtual environments demonstrate significant improvements in communication and collaboration skills compared to traditional teaching methods (Kuanbayeva et al., 2024). These technologies create interactive and enjoyable learning experiences that contribute to improved academic performance and higher levels of student satisfaction in science education (Kuanbayeva et al., 2024).

However, several challenges must be addressed to maximize the effectiveness of these technologies in educational settings. Technical issues, such as inadequate internet coverage and limited content availability, can hinder successful implementation (Subran & Mahmud, 2024), while inconsistencies in AR implementation for science experiments can affect outcome reliability (Syskowski et al., 2024). Additionally, research emphasizes the importance of understanding teachers' perspectives and providing adequate training to ensure successful integration of these technologies. These technologies should complement rather than replace traditional teaching methods, with careful consideration given to aligning their use with student needs and interests (Poveda-Mora et al., 2024).

4. Methodology

4.1. Population and Sample

The population comprised second-grade students at Kitiya Maha Sarakham School. Using stratified random sampling, 60 students were selected and equally divided into three groups of 20 students each: VR group (experimental group 1), AR group (experimental group 2), and control group.

4.2. Research Instruments

In order to expedite the acquisition and analysis of data, this investigation implemented numerous research instruments. The principal instruments were two educational applications: AR Solar Jelly and VR Solar Jelly. These applications were designed with a wide range of features, such as interactive learning activities, informative audio narrations, dynamic simulations of planetary motion, and three-dimensional planetary models. In order to evaluate the learning outcomes, we implemented a collection of achievement assessments. These consisted of a pre-test to determine the students' prior knowledge, a post-test to assess the extent of their learning, and a retention test administered two weeks following the instruction to assess their ability to recall the material. Furthermore, we obtained quantitative feedback on the learning experience by administering a questionnaire that utilized a five-point Likert scale to assess student satisfaction.

The AR Solar Jelly and VR Solar Jelly applications represent custom-developed educational tools built on the Unity3D platform, specifically designed to enhance astronomy education for primary school students. The AR application employs marker-based tracking technology, enabling students to engage with comprehensive three-dimensional models of planetary bodies through their tablet devices. This innovative application features meticulously detailed 3D models of all planets, complete with realistic textures and proportionally accurate representations. Students can observe and interact with dynamic simulations that accurately demonstrate planetary orbits and rotations, providing a clear visualization of celestial mechanics. To enhance accessibility and understanding, the application includes bilingual audio narrations in both Thai and English, complemented by interactive quizzes and learning activities that provide immediate feedback to support the learning process.

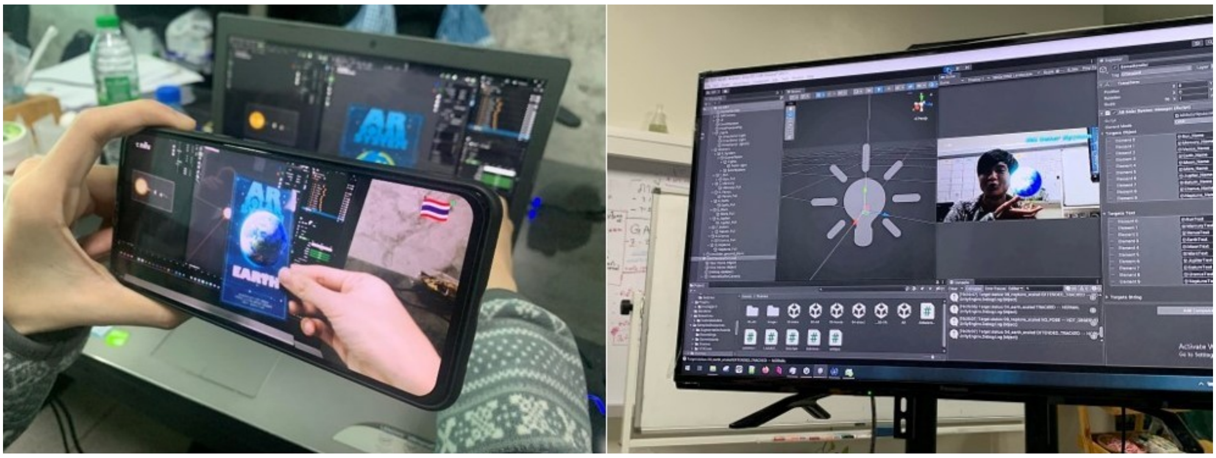

Figure 1. Screenshot of AR Solar Jelly application showing interactive planetary model

The VR component of the system delivers an even more immersive educational experience through standalone VR headsets. This application transforms traditional astronomy education by offering students a complete 360-degree exploration of the solar system, allowing them to virtually navigate through space while accessing interactive information displays about various celestial objects. The experience is further enhanced by guided educational tours that provide structured learning pathways, supported by an intuitive voice-activated navigation system. To monitor and encourage student progress, the application incorporates a comprehensive achievement tracking system that records and rewards learning milestones.

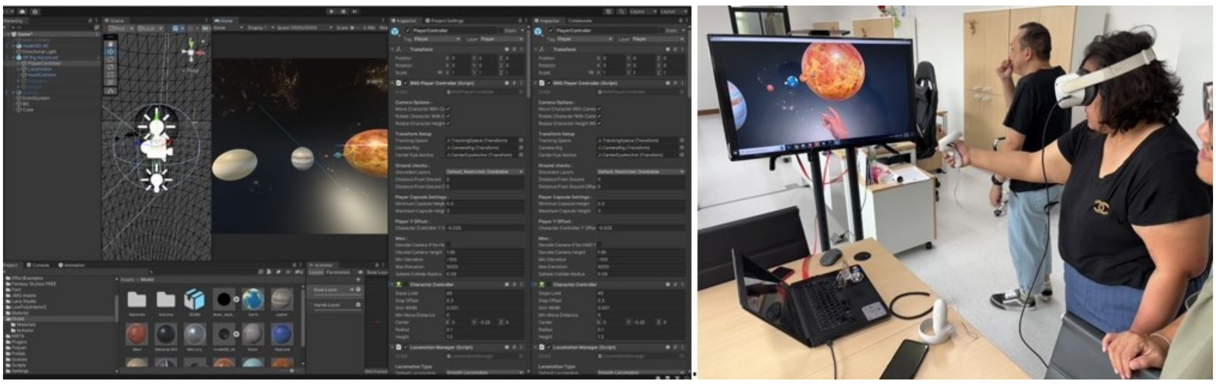

Figure 2. Screenshot of VR Solar Jelly application showing immersive solar system environment

4.3. Validity and Reliability of Research

The research instruments underwent rigorous validation processes:

1. Content validity: Three experts in astronomy education and educational technology evaluated the content
2. Construct validity: Pilot testing with 30 students from a similar demographic
3. Reliability testing: Cronbach's alpha coefficients for all assessment tools (Pre-test: 0.82, Post-test: 0.85, Satisfaction questionnaire: 0.88)

4.4. Data Collection

We conducted the data acquisition process in a systematic experimental manner over a period of six weeks. We initially administered a pre-test to all participating groups to determine their baseline knowledge levels. Subsequently, there was a four-week implementation phase. Experimental Group 1 acquired knowledge through the VR Solar Jelly app, Experimental Group 2 acquired knowledge through the AR Solar Jelly app, and the Control Group acquired knowledge through conventional methods. We administered an immediate post-test to all groups to assess their learning achievement following the completion of the implementation phase. In order to assess their experiences with the respective technologies, the experimental groups subsequently completed satisfaction assessments. Two weeks following the conclusion of instruction, we administered a learning retention test to assess the retention of knowledge across all groups.

4.5. Data Analysis

The collected data were analyzed using both descriptive and inferential statistical methods, with a significance level set at $\alpha = .05$ for all analyses. Descriptive statistics, including means (M) and standard deviations (SD), were calculated for pre-test, post-test, retention test, and satisfaction questionnaire scores. To compare learning achievement across the three instructional groups (VR, AR, and Control), a one-way Analysis of Covariance (ANCOVA) was conducted. Pre-test scores were used as a covariate to control for potential pre-existing differences in students' prior knowledge of the solar system. Prior to conducting the ANCOVA, preliminary assumption checks were performed to verify normality, linearity, homogeneity of variances, and homogeneity of regression slopes.

Following a statistically significant main effect, post-hoc pairwise comparisons with Bonferroni adjustment were employed to identify specific differences between groups. Effect sizes for the ANCOVA were reported using partial eta squared (η^2p), with values interpreted according to Cohen's (1988) guidelines: small (0.01), medium (0.06), and large (0.14). For pairwise comparisons, Cohen's d effect sizes were calculated and interpreted as small ($d = 0.2$), medium ($d = 0.5$), and large ($d = 0.8$). To examine knowledge retention within each group, paired-sample t-tests were conducted to compare immediate post-test scores with retention test scores administered two weeks after the intervention. Retention rates were calculated as percentages using the formula: (mean retention test score / mean post-test score) × 100.

Student satisfaction was assessed only in the VR and AR groups, as the questionnaire was specifically designed to measure perceptions of immersive technology-based learning and was not applicable to the traditional instruction conditions. Student satisfaction data from the VR and AR groups were analyzed using descriptive statistics (means and standard deviations) for each of the four dimensions: media interest, ease of use, interactivity, and entertainment. Mean satisfaction scores were interpreted using the following criteria: 2.34-3.00 = High, 1.67-2.33 = Moderate, and 1.00-1.66 = Low. All statistical analyses were performed using SPSS (Version 28.0).

4.6. Ethical Considerations

This study was conducted in accordance with standard ethical practices for research involving minor participants. Prior to the commencement of the experiment, formal permission was obtained from the school administrators of Kitiya Maha Sarakham School to implement the classroom-based intervention as part of the regular science curriculum. Written informed consent was secured from the parents or legal guardians of all participating students after they were fully informed about the nature and purpose of the study. Additionally, verbal assent was obtained from the students themselves before participating.

Participation was entirely voluntary, and all students were clearly informed that they could withdraw from the study at any time without any academic penalties or consequences. To ensure confidentiality, all data collected were anonymized and used solely for research purposes. As this study involved an educational innovation activity integrated into the standard curriculum and did not include any medical or psychological interventions, formal approval from an institutional ethics committee was not required in accordance with the policies of Rajabhat Mahasarakham University.

5. Results

5.1. Learning Achievement Comparison

Descriptive statistics were used to summarize students' learning achievement across the three instructional groups based on pre-test and post-test assessments, with a maximum achievable score of 20 points. Improvements in post-test scores were observed within all groups following the instructional intervention. Table 1 presents the pre-test, and post-test means and standard deviations for each group, along with the results of within-group comparisons.

Group	n	Pre-test		Post-test		t	p
		M	SD	M	SD		
VR group	20	5.65	1.53	16.90	0.97	43.22	<.001
AR group	20	5.30	1.26	15.40	1.57	25.04	<.001
Control group	20	5.25	0.97	12.40	1.43	26.09	<.001

Table 1. Comparison of Pre-test and Post-test Scores Within Groups

Paired-sample t-tests indicated that students in all three instructional conditions demonstrated statistically significant improvements from pre-test to post-test ($p < .001$). These results suggest that learning gains occurred in each group after the instructional period. However, because potential baseline differences in prior knowledge may influence post-test outcomes, inferential comparisons between instructional methods were not based on raw post-test means. Instead, adjusted post-test means derived from ANCOVA were used to compare learning achievement across groups, as reported in Section 5.2.

5.2. Comparison of Learning Achievement Between Groups Using ANCOVA

A one-way Analysis of Covariance (ANCOVA) was conducted to compare post-test learning achievements among the three instructional groups (VR, AR, and Control), using pre-test scores as a covariate to control baseline differences in prior knowledge. The results revealed a statistically significant effect of instructional method on post-test learning achievement, $F(2,56) = 62.87$, $p < .001$, $\eta^2 p = 0.69$, after adjusting for pre-test scores. The covariate (pre-test scores) was also found to be a significant predictor of post-test performance, $F(1,56) = 11.18$, $p = .001$, $\eta^2 p = 0.17$.

Source of Variation	SS	df	MS	F	p-value	$\eta^2 p$
Pre-test (Covariate)	17.21	1	17.21	11.18	.001	0.17
Instructional Method	193.82	2	96.91	62.87	**< .001**	**0.69**
Error	86.35	56	1.54			
Total	297.38	59				

Table 2. ANCOVA results for post-test scores by instructional group with pre-test scores as a covariate

Adjusted post-test means derived from ANCOVA were used to compare learning achievements across the instructional groups after controlling baseline differences in prior knowledge. The VR group demonstrated the highest adjusted post-test score (Madj = 16.78), followed by the AR group (Madj = 15.33) and the control group (Madj = 12.41).

Group	Estimated Mean (Madj)	Std. Error
VR	16.78	0.21
AR	15.33	0.24
Control	12.41	0.23

Table 3. Adjusted Post-test Means by Instructional Method after Controlling for Pre-test Scores (ANCOVA)

Following the significant ANCOVA result, Bonferroni-adjusted pairwise comparisons were conducted to examine differences in adjusted post-test learning achievement among the instructional groups. The results indicated that both the Virtual Reality (VR) and Augmented Reality (AR) groups achieved significantly higher adjusted post-test scores than the control group ($p < .001$). Furthermore, the VR group demonstrated significantly higher adjusted post-test scores than the AR group ($p = .004$), indicating that the VR-based instructional approach produced significantly higher adjusted post-test achievement after controlling baseline differences in prior knowledge.

Comparison	Adjusted Mean Difference	Std. Error	Bonferroni p	95% CI Lower	95% CI Upper
VR – AR	1.35	0.40	.004	0.37	2.32
VR – Control	4.33	0.40	< .001	3.35	5.30
AR – Control	2.98	0.39	< .001	2.01	3.95

Table 4. Bonferroni-Adjusted Pairwise Comparisons of Adjusted Post-Test Scores (ANCOVA)

5.3. Learning Retention Analysis

A comparative analysis was conducted to evaluate the retention of learning across the three instructional approaches two weeks after the completion of instruction. The analysis revealed notable differences in learning retention among the groups, with both technology-enhanced learning groups demonstrating superior retention rates compared to the traditional instruction group.

Group	Immediate Post-test		After 14 Day		Retention Rate
	M	S.D.	M	S.D.	
VR group	16.90	0.97	15.45	1.19	91.42%
AR group	15.40	1.57	13.75	1.59	89.29%
Control group	12.40	1.43	9.85	1.46	79.44%

Table 5. A Comparison of Learning Retention Scores (14 Day After Instruction)

These results showed that the VR group was able to maintain the highest retention rate, at 91.42%, throughout the experiment. The mean scores decreased from 16.90 to 15.45 over the two-week period. For the AR group, the retention rate was high as well; mean scores dropped from 15.40 to 13.75. The retention percentage of this cohort was 89.29%. Conversely, the control group's retention rate was a mere 79.44%, and their mean scores decreased from 12.40 to 9.85 over the same time frame. These results suggest that AR and VR technologies have the potential to improve learning retention in comparison to traditional instructional methods. The technology-enhanced groups' higher retention rates suggest that immersive learning experiences may lead to more enduring learning outcomes. This pattern is consistent with the theoretical predictions regarding the advantages of interactive and immersive learning environments in terms of knowledge retention.

5.4. Analysis of Students' Satisfaction

The satisfaction questionnaire was specifically designed to evaluate students' perceptions of immersive technology-based learning experiences, focusing on dimensions such as media interest, ease of use, interactivity, and entertainment. As the control group received traditional classroom instruction without the use of VR or AR applications, administering this instrument to the control group was not applicable. Therefore, satisfaction analysis was conducted exclusively for the VR and AR groups.

The analysis of student satisfaction with VR and AR learning experiences revealed interesting patterns across multiple dimensions. The VR group demonstrated consistently high satisfaction levels across all evaluated aspects, with mean scores ranging from 2.55 to 2.90. The highest satisfaction in the VR group was observed with Media Interest (M= 2.90, SD = 0.31), followed by Interactivity (M = 2.70, SD = 0.47). The relatively low standard deviations in the VR group (ranging from 0.31 to 0.59) suggest consistent responses among students.

	VR group			AR group		
Evaluation Aspects	M	S.D.	Satisfaction Level	M	S.D.	Satisfaction Level
Media Interest	2.90	0.31	High	2.65	0.49	High
Ease of Use	2.55	0.51	High	2.35	0.59	High
Interactivity	2.70	0.47	High	2.20	0.83	Moderate
Entertainment	2.65	0.59	High	2.35	0.75	High
Overall	2.85	0.37	High	2.65	0.49	High

Table 6. Analysis of Students' Satisfaction Towards Learning Experience

The AR group also showed generally high satisfaction levels, though with slightly lower mean scores ranging from 2.20 to 2.65. Media Interest received the highest satisfaction rating (M = 2.65, SD = 0.49), while Interactivity showed moderate satisfaction (M = 2.20, SD = 0.83). The higher standard deviations in the AR group, particularly for Interactivity (SD = 0.83), indicate more varied student responses compared to the VR group. Overall satisfaction was high for both groups, with the VR group showing slightly higher overall satisfaction (M = 2.85, SD = 0.37) compared to the AR group (M = 2.65, SD = 0.49). These findings suggest that while both technologies were well-received, the VR implementation may have provided a more consistently engaging learning experience across all evaluated aspects.

6. Discussion

The findings of this study provide empirical evidence supporting the effectiveness of immersive technologies in primary science education. After controlling for baseline differences in prior knowledge using pre-test scores as a covariate, the ANCOVA results revealed a statistically significant effect of instructional method on post-test learning achievement, $F(2,56) = 62.87$, $p < .001$, $\eta^2p = 0.69$. Post-hoc Bonferroni-adjusted comparisons indicated that both the VR ($M_{adj} = 16.78$) and AR ($M_{adj} = 15.33$) groups achieved significantly higher adjusted post-test scores than the control group ($M_{adj} = 12.41$). Furthermore, the VR group demonstrated significantly higher adjusted post-test performance than the AR group ($p = .004$). These findings highlight the importance of controlling prior knowledge when evaluating the effectiveness of technology-enhanced instructional interventions.

The superior adjusted performance observed in both immersive learning conditions may be attributed to the affordances of VR and AR technologies in facilitating the visualization of abstract astronomical concepts. Immersive environments allow learners to observe and manipulate three-dimensional representations of planetary systems, which can support conceptual understanding and reduce cognitive difficulties typically associated with spatial reasoning in astronomy education. The significantly higher adjusted achievement scores observed in the VR group suggest after controlling pre-test scores that fully immersive environments may provide additional learning benefits by minimizing external distractions and enhancing learner engagement within a controlled virtual context.

The retention analysis further demonstrated that students in both immersive learning groups maintained higher levels of post-intervention performance compared to those receiving traditional instruction after a two-week interval. This finding suggests that experiential and multisensory learning environments may contribute to more durable knowledge structures. In addition, the satisfaction analysis indicated consistently higher levels of engagement among students in the VR and AR groups, with the VR group reporting the highest overall satisfaction.

Despite these promising findings, several limitations should be acknowledged. The relatively small sample size (N = 60) may limit the generalizability of the results, and the six-week intervention period may not fully capture the long-term impact of immersive technologies on student learning outcomes. Additionally, potential novelty effects associated with the introduction of new technologies may have influenced student engagement. Future research should replicate this study across larger and more diverse samples, examine long-term retention outcomes, and explore moderating variables that may influence the effectiveness of immersive learning environments across different science domains. From the perspective of technology and science education at the higher education level, this study carries important implications for teacher preparation programs and educational technology development curricula. Pre-service science and technology teachers, as well as instructional designers, must understand both the pedagogical affordances and technical constraints of immersive learning tools in order to design effective learning experiences across educational levels. The findings of this study provide empirical evidence that can be incorporated into higher education coursework focused on educational technology design, human-computer interaction in learning environments, and technology integration in K–12 science education. Furthermore, the development process of VR Solar Jelly and AR Solar Jelly illustrates a practical model for engineering and technology education students to apply software development skills within pedagogically grounded contexts, linking technical competency with real-world educational impact.

7. Conclusion

This study provides empirical evidence for the comparative effectiveness of Virtual Reality (VR) and Augmented Reality (AR) technologies in teaching astronomical concepts to primary school students. Using a quasi-experimental design with 60 students assigned to VR, AR, and traditional instruction groups, this study examined learning achievement, knowledge retention, and student satisfaction across three instructional approaches.

After controlling for baseline differences in prior knowledge using pre-test scores as a covariate, the ANCOVA results revealed a statistically significant effect of instructional method on post-test achievement, $F(2,56) = 62.87$, $p < .001$, $\eta^2p = 0.69$. Post-hoc Bonferroni-adjusted comparisons indicated that both the VR (Madj = 16.78) and AR (Madj = 15.33) groups achieved significantly higher adjusted post-test scores than the control group (Madj = 12.41). Furthermore, the VR group demonstrated significantly higher adjusted achievement than the AR group, suggesting that fully immersive learning environments may offer additional pedagogical benefits in supporting conceptual understanding of abstract astronomical content. In addition, students in both immersive learning conditions demonstrated higher retention of learning outcomes after a two-week interval compared to those receiving traditional instruction. Satisfaction analysis also indicated consistently higher levels of engagement in the VR and AR groups, with the VR group reporting the highest overall satisfaction.

These findings suggest that immersive instructional technologies, particularly VR, can enhance students' understanding and retention of complex scientific concepts when prior knowledge is appropriately controlled. The results support the integration of immersive learning environments into primary science education, while highlighting the importance of teacher preparation and infrastructure readiness to ensure effective implementation. Future research should explore long-term learning outcomes and examine the effectiveness of immersive technologies across different scientific domains and learner characteristics. At the higher education level, this work also invites educators in technology and engineering fields to examine how the design, development, and evaluation of immersive educational applications can serve as authentic project-based learning contexts, bridging technical skills development with meaningful educational outcomes.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

Authors' contributions

Potsirin Limpinan: Conceptualization, methodology, supervision, coordination of the research project, and writing original draft preparation. Data collection, software development, and technical implementation of the VR applications. Formal analysis, data visualization

Weerapat Pichetphon: Data collection, software development, and technical implementation of the AR applications.

Thanet Yuensook: Formal analysis and visualization.

Thada Jantakoon: Validation of the research design, manuscript review, and academic guidance.

Data availability

Data available upon request

Use of Artificial Intelligence

The authors declare that artificial intelligence was used for linguistic editing and language improvement only. The intellectual content and research design were entirely developed by the authors.

References

Alizadeh, M. (2024). Innovative pedagogical models in immersive learning environments: A case study of flipped classrooms. *Educational Technology Research and Development, 72*(1), 89–104.

Cabrera-Duffaut, A., Martinez, R., & Lee, K. (2024). Virtual reality applications in higher education: Developing critical competencies. *Higher Education Research & Development, 43*(2), 178–193.

Carneiro, A. C. de O., Paillard, G., Neto, J. P., Vidal, C. A., Cavalcante-Neto, J. B., Leite, A. J. M., & Gomes, A. C. (2024). Virtual reality in astronomical education: Improving the understanding of eclipses with interactive simulations. *Proceedings of the XXVI Symposium on Virtual and Augmented Reality (SVR)*, (pp. 112–120). Brasil. https://doi.org/10.5753/svr_estendido.2024.244743

Chiang, C. L., Lin, Y. L., Chao, H. C., Chen, J. Y., & Lai, C. H. (2019). Effect of augmented reality on astronomical observation instruction. In *International Conference on Innovative Technologies and Learning* (pp. 123–132). Springer. https://doi.org/10.1007/978-3-030-35343-8_20

Cohen, J. (1988). *Statistical Power Analysis for the Behavioral Sciences* (2nd ed.). Hillsdale, NJ: Lawrence Erlbaum Associates, Publishers.

Demitriadou, E., Stavroulia, K. E., & Lanitis, A. (2020). Comparative evaluation of virtual and augmented reality for teaching mathematics in primary education. *Education and Information Technologies*, *25*(1), 381–401. https://doi.org/10.1007/s10639-019-09973-5

Ercoşkun, M. H., İspir, B., & Yıldız, A. (2024). The use of augmented reality, virtual reality and mixed reality technologies in education: A bibliometric and systematic review. *Eğitimde Nitel Araştırmalar Dergisi*, *40*(2), 245–267. https://doi.org/10.14689/enad.40.1918

Fleck, S., & Simon, G. (2013). An augmented reality environment for astronomy learning in elementary grades: An exploratory study. *Proceedings of the 25th Conference on l'Interaction Homme-Machine* (pp. 14–22). New York. https://doi.org/10.1145/2534903.2534907

Gunčaga, J., Korenova, L., & Severini, E. (2024). Enhancing STEAM education with AR: A primary education teacher training study. *Proceedings of the European Conference on e-Learning, 23*(1), 114–121. https://doi.org/10.34190/ecel.23.1.2692

Kapralos, B. (2024). Hands-on learning through virtual reality: Applications in healthcare education. *Medical Teacher, 46*(4), 412–425. https://doi.org/10.1080/0142159X.2023.2286543

Kuanbayeva, B., Shazhdekeyeva, N., Zhusupkaliyeva, G., Mukhtarkyzy, K., & Abildinova, G. (2024). Investigating the Role of Augmented Reality in Supporting Collaborative Learning in Science Education: A Case Study. *International Journal of Engineering Pedagogy*, 14(1).

Lelliott, A., & Rollnick, M. (2010). Big ideas: A review of astronomy education research 1974-2008. *International Journal of Science Education*, *32*(13), 1771–1799. https://doi.org/10.1080/09500690903214546

Mahmoudi-Dehaki, M., & Nasr-Esfahani, N. (2024). Educational virtual reality (VR). In *Advances in Educational Technologies and Instructional Design* (pp. 89–115). IGI Global. https://doi.org/10.4018/9798369364079.ch005

Plummer, J. D. (2014). Spatial thinking as the dimension of progress in an astronomy learning progression. *Studies in Science Education*, *50*(1), 1–45. https://doi.org/10.1080/03057267.2013.869039

Poveda-Mora, S., Martinez, R., & Chen, H. (2024). Virtual and augmented reality in elementary science education: Impact on learning outcomes. *Educational Technology Research and Development, 72*(1), 45–62.

Subran, N., & Mahmud, R. (2024). Motivational effects of AR/VR technologies in science education. *Interactive Learning Environments, 32*(3), 567–582. https://doi.org/10.1080/10494820.2023.2184125

Syskowski, P., Wilson, J., & Thompson, L. (2024). Implementation challenges of AR in science experiments: A systematic review. *Journal of Science Education and Technology, 33*(2), 189–204. https://doi.org/10.1007/s10956-023-10062-2

Szentirmai, V. (2024). Universal design principles in VR educational applications. *International Journal of Virtual Reality, 23*(2), 156–171. https://doi.org/10.20870/IJVR.2024.23.2.1234

Tene, O., Kumar, S., & Zhang, Y. (2024). Immersive technologies in higher education: Enhanced understanding through virtual experiences. *Higher Education Studies, 14*(1), 112–127. https://doi.org/10.5539/hes.v14n1p112

Vosniadou, S., & Brewer, W. F. (1992). Mental models of the earth: A study of conceptual change in childhood. *Cognitive Psychology*, *24*(4), 535–585. https://doi.org/10.1016/0010-0285(92)90018-W

Zhang, J., Sung, Y. T., Hou, H. T., & Chang, K. E. (2014). The development and evaluation of an augmented reality-based armillary sphere for astronomical observation instruction. *Computers & Education, 73,* 178–188. https://doi.org/10.1016/j.compedu.2014.01.003

Zuo, R., Wenling, L., & Xuemei, Z. (2025). Augmented reality and student motivation: A systematic review (2013–2024). *Journal of Computers for Science and Mathematics Learning, 2*(1), 38–52. https://doi.org/10.70232/jcsml.v2i1.23

Published by OmniaScience (www.omniascience.com)

Journal of Technology and Science Education, 2026 (www.jotse.org)