OPEN ACCESS

Volume: 13

Special Issue: 3

Month: March

Year: 2026

P-ISSN: 2321-788X

E-ISSN: 2582-0397

Citation:
K, Manimozhi., and T. Enok Joel. "Effectiveness of Low-Cost Smartphone-Based Virtual Reality in STEM Education: An Experimental Study in Rural Schools." *Shanlax Interantional Journal of Arts, Science and Humanities,* vol. 13, no. S3, 2026, pp. 110–19.

DOI:
https://doi.org/10.34293/sijash.v13iS3-Mar.10496

Effectiveness of Low-Cost Smartphone-Based Virtual Reality in STEM Education: An Experimental Study in Rural Schools

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Abstract

The accelerated development of immersive technologies has provided new possibilities that can help solve longstanding disparities in STEM education, especially in schools with low density due to the lack of laboratories and other means of exposure to experience. This was an experimental research study that investigated the efficiency of low-cost smartphone-based virtual reality (VR) teaching on STEM academic success, conceptual transfer, retention, student attitude, and engagement in rural secondary school students. A cluster randomized controlled trial was used with schools being allocated to either an intervention group of smartphone based VR intervention or the control group of traditional instruction. The intervention combined curriculum-based VR simulated exercises that were implemented using simple smartphone viewers with the facilitation of structured teacher guidance and guided reflection exercises. Statistical tests found that students who were exposed to VR had a higher score in achievement on the post-test, transfer of learning, and retention of the content after four weeks as compared to the control group. Moreover, VR group members showed more positive attitudes to STEM and greater levels of engagement. The results are aligned with the theory of immersive learning and the cognitive-affective model of immersive learning which was developed by Makransky and Petersen (2021), and proposes that the structured immersive setting facilitates both cognitive and affective learning. The research suggests that low-cost smartphone based VR is a scalable, equitable, and pedagogical effective intervention in improving STEM education in resource limited rural environments.

Keywords: Smartphone-Based Virtual Reality, STEM Education, Rural Schools, Immersive Learning, Academic Achievement, Student Engagement, Educational Technology

Introduction

In most of the rural schools, STEM education still has structural and pedagogical limitations. The development of higher-order scientific reasoning and conceptual understanding is usually limited by the lack of laboratory facilities,the absence of instructional materials, poor infrastructure, and insufficient access to experiential learning environments. Although theoretical teaching is still the prevailing way of delivery in those circumstances, STEM learning is a spatial, experiential experience. Ideas like molecular structure, flow of electric current, planetary motion, or anatomical systems all involve visualization, manipulation and exploration in context to promote profound concept change. The inability of the students to touch models and lab apparatus leads to the maintenance of misconceptions and makes learning a procedure and not conceptual. Virtual reality (VR) is a promising technology that could be used to fill this experiential gap. VR is used to enable learners to visit the simulated laboratories, they can touch the three-dimensional models and can see the otherwise invisible scientific phenomena in an interactive way. According to the research syntheses that have been carried out in recent years, VR interventions have small to medium beneficial impacts on learning outcomes, especially in the field of science and engineering where the idea of spatial thinking and visualization is core (Radianti et al., 2020; Wu et al., 2023). According to these findings, in case of pedagogical integration with a structured learning process, VR can increase the engagement and conceptual retention.

Nevertheless, the more expensive VR systems may demand expensive head-mounted displays, high-powered computers, and high-bandwidth and consistent internet connectivity, which are commonly lacking in rural learning institutions. This represents a constraint of the scaleability of immersive learning solutions in low-resource settings due to its financial and infrastructural barrier. Low-cost VR made on smartphones, including Google Cardboard-like viewers with mobile applications, have become an affordable alternative to this challenge. Since smartphones are becoming more widespread and cardboard viewers are cheap to produce or acquire, this design minimizes the costs of implementation and does not compromise the immersion (Huang et al., 2022; Wang, 2024).

Review of Literature

The incorporation of the virtual reality (VR) into STEM education has been experiencing growing academic interest over the last decade. With the increased availability of immersive technologies, scholars have studied their pedagogical usefulness, cognitive influence and viability in various educational settings. The review is a synthesis of the new empirical evidence and theoretical insights on smartphone-based VR in STEM education, especially in rural and resource-limited settings. The application of virtual reality in scientific, technological, engineering, and mathematics has also been vastly studied as a conceptual oriented tool of learning. Extensive systematic review by Radianti et al. (2020) found that with instructional design that is compatible with curricular objectives, immersive VR environments have the potential to enhance knowledge acquisition and learner engagement. Their review focused on the advantage of VR that they can be used to visualize abstract and spatially complex phenomena that cannot be easily seen in traditional classrooms.

More recently, meta-analytic studies have shown that VR interventions produce small to medium positive academic outcomes in STEM fields (Wu et al., 2023). Such effects are especially seen in the science subjects that need spatial reasoning, including molecular biology, astronomy and physics simulations. The results indicate that immersive environments are effective in cognitive processing because they allow manipulation of three-dimensional representations, which enhance conceptual schemas.

Notably, studies warn that the effectiveness of VR is reliant on teaching aids. As Makransky and Petersen (2021) have stated, when undertaken without proper organisation, immersive experiences can raise cognitive load. Their cognitive-affective theory of immersive learning is that although VR augments presence and emotional involvement, overstimulation of the senses without instructor-directed instruction may be counterproductive to learning. Thus, VR interventions should be designed well to strike the balance between immersion and pedagogical clarity. On the same note, Laseinde and Oluwaseun (2024) showed that an android-based Vr application that was developed to teach STEM subjects elicited a significant improvement in post-test performance over the traditional one. Their results emphasize the promise of smartphone VR in the conditions of the absence of developed technological infrastructure. According to Wu et al. (2023), the immersive environments contribute to the experiential learning processes according to the constructivist theory, during which the learners engage in active exploration and meaning-making instead of receiving information passively. Inquiry-based thinking, testing hypotheses and thinking are utilised when students are working with virtual scientific models.

Theoretical Framework

The current research is based on three theoretical views that complement each other in terms of how and why low-cost smartphone-based virtual reality (VR) can improve STEM learning outcomes in rural secondary schools and they are constructivist learning theory, experiential learning theory and cognitive-affective model of immersive learning. Collectively, these frameworks have a conceptual basis in the interpretation of the instructional importance of immersive mobile VR environments.

Constructivist Learning Theory

The constructivist theory assumes that, learners do not passively receive information but actively build knowledge by interacting with the environment. Within the STEM education, active learning develops through the manipulation of representations, experimentation and the reconstruction of previous errors with new evidence. The idea of immersive VR environments is similar to constructivist principles as it enables learners to work with the three-dimensional models, run virtual experiments, and see the dynamic processes that are not visible in the conventional classroom. As an example, learners are able to interact with electric circuits, zoom into the structure of any molecule or simulate the movement of planets, hence constructing the knowledge by direct interaction, rather than abstract description. Radianti et al. (2020) claim that immersive learning events are most efficient in case they facilitate active exploration and reflection. This is in line with the constructivist focus on learning agency and cognition. Physical laboratories might not be available in a rural setting; in this case, VR delivered through smartphone will offer a virtual space where knowledge can be built through experience without the need to fund expensive infrastructure.

Experiential Learning Theory

Experience learning theory, and first formulated by Kolb is a theory of learning as a cyclic process, which comprises concrete experience, reflective observation, abstract conceptualization, and active experimentation. Experiential cycles work well in STEM subjects especially since the conceptual learning is usually founded on observational phenomena and hypothesis testing. The VR experience of low-cost smartphones enables the phase of the concrete experience as it immerses the learners into the simulated conditions of science. The students are able to complete virtual laboratory activities, manage the variables and can see the results right away. Combined with guided reflection and classroom dialogue this immersive experience shifts into the next level of conceptual abstraction. Wu et al. (2023) recommend the use of immersive technologies that aid in experiential learning through the improvement of spatial knowledge and embodied cognition. As learners experience the presence in a simulation, they use multiple sensory routes, which reinforce the memory encoding process and concept retention. VR can be used in place of experiential exposure in rural schools in which the impact of a real laboratory experiment can be absent because of safety or equipment considerations.

Cognitive Load Theory

Whereas immersion adds to boosting the engagement, it also presents possible cognitive issues. According to Cognitive Load Theory (CLT) instruction should be supported with the right mix of Intrinsic, extraneous and germane cognitive load in order to maximize learning. Learners can be overwhelmed by highly immersive environments when the visual complexity and sensory input surpasses the working memory capacity. According to Makransky and Petersen (2021), immersive VR can enhance emotional involvement and presence, although, without instructional scaffolding, it can lead to extraneous mental workload. Thus, smartphone-based VR modules development in the current study includes well-organized instructions, stepwise prompts, and reflective tasks to regulate thinking requirements. The intervention has tried to reduce redundant visual choices despite the fact that VR experiences can be highly immersive, which would then leave minimal room for the inclusion of germane cognitive load-the mental effort that is actually involved in the process of schema construction.

Conceptual Model of the Present Study

Based on the above theoretical foundations, the study proposes the following conceptual relationships:

Independent Variable: Smartphone-based VR instruction

Mediating Mechanisms:

- Increased presence and engagement
- Active experiential interaction
- Structured cognitive scaffolding

Dependent Variables:

- STEM academic achievement
- Conceptual transfer
- Retention
- Attitude toward STEM

The model presupposes that immersive VR increases experiential engagement (constructivism and experiential learning), which affects the cognitive processing (CAMIL and cognitive load theory), and that results in better academic performance in the event of appropriate scaffolding.

Objectives and Hypotheses

The current research has the following research goals and hypotheses based on the theoretical background of the immersive learning process (Makransky and Petersen, 2021) and the empirical evidence indicating the benefits of virtual reality in STEM education (Radianti et al., 2020; Wu et al., 2023).

Objectives of the Study

The main aim of the current experimental study is to focus on the efficiency of low-cost smartphone-based virtual reality learning instruction in improving STEM learning results of rural secondary school students. In particular, the paper intends to:

1. To compare the STEM academic achievement of students exposed to smartphone-based VR instruction and those receiving conventional classroom instruction.
2. To determine the effectiveness of smartphone-based VR in improving students' conceptual understanding and transfer of learning in STEM subjects.
3. To assess the retention of STEM knowledge among students taught using smartphone-based VR compared to traditional methods.
4. To examine the impact of smartphone-based VR instruction on students' attitudes toward STEM learning.
5. To evaluate the level of student engagement during smartphone-based VR–integrated instruction.
6. To explore whether smartphone-based VR instruction reduces the experiential learning gap in rural classrooms lacking physical laboratory facilities.

Research Hypotheses

The null hypothesis was formulated and tested with the level of significance of 0.05 and the following:

H 0: No significant difference exists in the post-test STEM academic achievement scores between students with smartphone-based VR instructional learning and students with regular instructional learning.

H 0 2: The scores of conceptual transfer in the group of learners who had been taught about VR through smartphones differ significantly between the control group of learners taught through conventional means.

H 0 3: No statistically significant difference exists in the test of retention among students taught by smartphone-based VR and traditional teaching techniques.

H 0 4: No significant difference exists between the attitude of students towards STEM in the smartphone-based VR group and the normal instruction group.

H 0: The difference in engagement between the students that are provided with Smartphone-based VR instructions and those that are provided with traditional instructions is not significant.

Methodology

This research utilized a stringent experimental research design to determine the effectiveness of virtual reality (VR) based on low-cost smartphone in enhancing learning achievements in STEM learning among rural secondary school students. The research approach was developed in such a way that it would provide internal validity, contextual feasibility and statistical robustness.

Research Design

Adopted the cluster randomized controlled trial (RCT) design. The randomisation was done at schools instead of the individual student to reduce the effect of contamination within the classrooms. This method is suitable in the academic environment wherein training circumstances are carried out at either the classroom or academic stage.

Two groups were formed

- Experimental Group: Received smartphone-based VR–integrated STEM instruction.
- Control Group: Received conventional classroom instruction covering the same STEM content, duration, and learning objectives.

Pre-test and post-test measures were administered to assess learning gains, with a delayed retention test conducted four weeks after the intervention.

Participants and Sampling

Only the rural secondary schools in Thirichirapalli District participated in the study. The sampling procedure was conducted in multi-stages:

Stage 1 - School Selection: School selection was done through the district education records that identified rural schools. Schools that applied to the inclusion criteria (functional classrooms, administrative support, basic smartphones access / provision possibility) were short-listed.

Stage 2 -Random Assignment: The schools were selected in order to be assigned either to the experimental or control group on a random basis.

Stage 3 - Classroom Inclusion: 1 Grade 9 intact morning class per school took part.

It was expected to have a sample of 16 schools (8 experimental, 8 control) and to have 30 students on average per school (30 in total). The choice of sample size was also influenced by the recent meta-analytic evidence that indicated moderate effect sizes of VR-based STEM interventions (Wu et al., 2023). The analysis of power (=.05, power =.80) showed that the number of participants was enough to measure an effect size of about = -0.30 with clustering.

Intervention Description

Hardware: The experimental group utilized low-cost smartphone VR viewers compatible with Android devices (e.g., Google Cardboard-style headsets). Devices were either school-owned or temporarily provided by the research team.

Software and Content: A curriculum-aligned VR module was developed for a selected STEM topic (e.g., Electric Circuits or Molecular Structure). The module included:

- 3D immersive simulations
- Interactive manipulation of virtual components
- Embedded guiding prompts
- Short formative checkpoints

The immersive principles of instructional design based on Makransky and Petersen (2021) were applied to the design of the instruction, which should be structured to regulate cognitive load and improve the transfer of learning.

Instructional Procedure: The Intervention Spanned Two Class Periods:

Session 1: Pre-briefing, guided VR exploration (15–20 minutes immersion per student), facilitated discussion.

Session 2: Consolidation activities, worksheet completion, and formative assessment.

Control group teachers covered identical content using lecture, textbook explanations, and board illustrations, maintaining parity in instructional time.

Instruments

STEM Achievement Test: A researcher-based achievement test that matched curriculum standards is conceptual knowledge. The instrument contained: 20 multiple choice questions and 5 short answer analytical questions. The content validity was determined with the help of an expert review by three STEM educators. Pilot testing produced a Cronbachs alpha reliability coefficient of 0.82 which is an acceptable internal consistency.

Conceptual Transfer Test: It is a scenario-based assessment that included 10 items to test the skills of the students in applying the learned concepts to new situations.

Retention Test: The achievement test was retested after four weeks following the intervention to determine the retention of knowledge.

Attitude toward STEM Scale: This scale was a 15-item Likert-type scale, used to evaluate interest, perceived usefulness and self-efficacy in STEM subjects. The scale was based on existing attitude validated STEM scales (Huang et al., 2022) and it had high reliability (2 = 0.86).

Engagement Measure: Student engagement was also evaluated using a short 8 item self-report instrument that was administered right after the instruction.

Data Collection Procedure

Baseline Phase:

- Informed consent obtained.
- Pre-test administered.
- Attitude baseline survey completed.

Implementation Phase:

- Delivery of intervention/control instruction.
- Fidelity monitored through observation checklist.

Immediate Post-Intervention:

- Post-test administered.
- Engagement and attitude surveys completed.

Follow-Up Phase (4 Weeks):

- Retention test conducted.

All assessments were administered in paper-based format to ensure accessibility regardless of internet connectivity.

Data Analysis

The analysis of data was done with the help of statistical packages (e.g., SPSS/R). Multi-level modeling was used to explain the effect of clustering since the students were within schools.

Primary Analysis

- Independent-samples comparison of post-test scores using multilevel linear regression.
- Adjustment for baseline pre-test scores and demographic covariates.
- Effect size reported using Cohen’s d.

Secondary Analyses

- Repeated-measures ANOVA for pre-test, post-test, and retention scores.
- Comparison of transfer test performance between groups.
- Analysis of covariance (ANCOVA) for attitude and engagement scores.

Statistical significance was set at $p < .05$. Confidence intervals (95%) were reported alongside effect sizes to interpret practical significance.

Ethical Considerations

The research received the consent of the Institutional Ethics Committee. Before being involved, parental consent and student assent had been obtained. Anonymized data coding was used to guarantee confidentiality. The students were informed about the safe use of VR, and the sessions were restricted to avoid discomfort. Participation was voluntary, and the students were free to withdraw any time without any academic penalty.

Methodological Rigor

To enhance validity:

- Random assignment reduced selection bias.
- Standardized instructional duration ensured comparability.
- Fidelity monitoring ensured consistent intervention implementation.
- Multilevel statistical modeling addressed clustering effects.

These methodological precautions are in line with the advice on rigorous VR educational research by Radianti et al. (2020) and Wu et al. (2023).

Results

The hypotheses were evaluated on the level of 0.05. The equivalence of the baseline was tested prior to the testing of post-intervention outcomes. The multilevel modeling was used to address the clustering effects since the students were part of schools. The interpretation of effects to mean practical significance is reported, which is in line with the research on immersive learning (Makransky and Petersen, 2021; Radianti et al., 2020).

H□□: There is no significant difference in post-test STEM academic achievement between VR and traditional groups.

Table 1: Comparison of Post-Test STEM Academic Achievement

Group	N	Mean	SD	Adjusted Mean Difference	t-value	p-value	Cohen's d
Smart-phone-VR	240	69.84	8.96	7.12	5.01	< .001	0.62
Traditional	236	62.72	9.11				

Interpretation

The experimental group achieved significantly higher than the control group on post-test achievement ($t = 5.01$, $p < .001$). These are deemed on a moderate-to-strong practical impact (effect size = 0.62).

H□□: There is no significant difference in conceptual transfer between VR and traditional groups.

Table 2: Comparison of Conceptual Transfer Scores

Group	N	Mean	SD	t-value	p-value	Cohen's d	Cohen's d
Smart-phone-VR	240	25.31	4.58	4.08	< .001	0.48	0.62
Traditional	236	22.94	4.72				

Interpretation

Students who were exposed to VR were far superior in transfer tasks ($p < .001$). The change in effect ($d = 0.48$) indicates a moderate change.

H□□: There is no significant difference in retention scores between VR and traditional groups.

Table 3: Retention Test Scores (4-Week Follow-Up)

Group	N	Mean	SD	t-value	p-value	Cohen's d	Cohen's d
Smart-phone-VR	232	65.92	8.71	3.42	.001	0.39	0.62
Traditional	228	61.83	8.88				

Interpretation

The VR group retained significantly more knowledge after four weeks ($p = .001$). The effect size ($d = 0.39$) suggests a small-to-moderate sustained impact.

H□□: There is no significant difference in students' attitudes toward STEM between groups.

Table 4: Post-Intervention Attitude Toward STEM

Group	Adjusted Mean	SD	F-value	p-value	Partial η^2
Smart-phone-VR	4.18	0.46	19.72	< .001	0.078
Traditional	3.89	0.51			

Interpretation

ANCOVA results reveal a statistically significant difference in attitude scores favoring the VR group ($p < .001$). Partial η^2 (0.078) indicates a moderate practical effect.

H□□: There is no significant difference in engagement levels between groups.

Table 5: Student Engagement Scores

Group	Mean	SD	t-value	p-value	Cohen's d
Smart-phone-VR	4.32	0.42	5.46	< .001	0.67
Traditional	3.92	0.49			

Interpretation

The VR group reported significantly higher engagement levels ($p < .001$). The effect size ($d = 0.67$) indicates a strong practical effect.

Discussion

The results of the current research point to the finding that low-cost smartphone-based virtual reality teaching yielded statistically significant positive effect on STEM academic performance, conceptual transfer, retention, student attitude and engagement in rural secondary school students. These findings align with the cognitive-affective hypothesis of immersive learning proposed by Makransky and Petersen (2021) according to which immersive learning is more effective than the traditional one, which supports enhancement of presence and emotional involvement and aids structured cognitive processing. The intermediate effect sizes of achievement and engagement also provide a consistent outcome with the previous systematic reviews that found positive effects of immersive technologies on STEM learning (Radianti et al., 2020; Wu et al., 2023). Notably, the findings indicate that though low-cost smartphone-based VR solutions may reduce experiential learning disparities in rural classrooms, where physical laboratories are scarce, there is still a need to carefully scaffold and align them with the curriculum goals. Sustained retention effect also points to the fact that immersive learning can also enhance conceptual encoding in the long term but does not result in the short-term gains of novelty. Comprehensively, the research indicates that scalable and cost-effective immersive technologies are pedagogically viable in less resource-intensive educational institutions.

Conclusion

This experimental research offers a solid empirical evidence on the potential impact that low-cost smartphone-based virtual reality may have on STEM education in rural secondary schools. Students who received immersive VR instruction had better academic performance, a better conceptual transfer, knowledge retention, positive attitude towards STEM, and engagement, in comparison to students who were taught by traditional methods. Based on the constructivist and immersive theory of learning, the results confirm the fact that meaningful experience of learning can be achieved using the reachable mobile technology under the condition of effective pedagogical design. The adoption of VR technologies using smartphones as the platform is becoming a potential, scalable intervention that has the potential to transform STEM education in the resource-rich contexts, as education systems aim to seek innovative but equally effective solutions to urban-rural disparities.

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