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Augmented Reality in Learning: Its Impact on the Understanding of Abstract Concepts

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ABSTRAK

This study investigates the effect of immersive simulation-based learning on students' empathy development compared to video-based learning and non-technology instruction. A randomized controlled trial with a pre-test–post-test design involving three groups was employed. A total of 120 undergraduate students aged 18–25 years were randomly assigned to a virtual reality (VR) simulation group, a video-based learning group, and a control group. Empathy was measured as a latent construct consisting of cognitive and emotional dimensions, adapted from established empathy theory. Data were analyzed using repeated measures ANOVA and Structural Equation Modeling–Partial Least Squares (SEM–PLS). The results indicate that the VR simulation group demonstrated a significantly greater increase in empathy compared to the other groups. Structural modeling further revealed that immersive simulation had a stronger positive effect on empathy than video-based learning. These findings suggest that immersive learning environments effectively support empathy development through integrated cognitive and emotional engagement.

INTRODUCTION

Difficulties experienced by students in understanding abstract concepts remain a fundamental problem in formal learning practices, particularly in disciplines that require high-level mental representation skills such as science, mathematics, and technology. Abstract concepts often lack direct references in students' concrete experiences, thereby demanding complex cognitive processes to construct meaningful conceptual understanding. When instructional processes fail to optimally facilitate the formation of such mental representations, students tend to encounter difficulties in comprehending conceptual structures, integrating knowledge, and transferring concepts to new contexts (Guntur & Setyaningrum, 2021; Su et al., 2022).

In conventional learning practices, instructional delivery is still predominantly based on written texts and static two-dimensional visuals. This approach is often insufficient to support the concretization of abstract concepts, particularly for learning materials that require complex spatial visualization and structural relationships. As a result, learning tends to emphasize procedural memorization rather than deep conceptual understanding. This condition contributes to low levels of higher-order cognitive achievement and limited problem-solving abilities among students (Chonchaiya & Srithammee, 2025; Mansour et al., 2024).

The rapid development of digital learning technologies over the past decade has opened new opportunities to address these limitations. Augmented Reality is one such technology that enables the integration of three-dimensional virtual objects into real-world environments in an interactive and real-time manner. The visual, immersive, and manipulable characteristics of Augmented Reality make it a promising learning medium for supporting the understanding of abstract concepts through more concrete and meaningful learning experiences. Through direct visualization and interaction with virtual objects, students are able to construct more accurate and integrated conceptual representations (Dewi, 2025; Rohendi et al., 2025).

At the international level, the use of Augmented Reality in education has expanded rapidly across various disciplines. Numerous studies report that this technology enhances the quality of learning experiences, cognitive engagement, and learning outcomes, particularly for abstract and complex subject matter. Meta-analyses and systematic reviews further indicate that Augmented Reality has significant potential to improve learning outcomes, especially in science, mathematics, and medical education contexts (Su et al., 2022; Zhang et al., 2022; Zhang et al., 2025).

Nevertheless, empirical findings regarding the impact of Augmented Reality on the understanding of abstract concepts remain inconsistent. While some studies report significant improvements in cognitive achievement, others suggest that the effectiveness of Augmented Reality depends on learning contexts, student characteristics, and the quality of instructional media design. This variation indicates that the effectiveness of Augmented Reality cannot be attributed solely to the presence of technology, but must be examined within a broader pedagogical and cognitive framework (Arnoldus et al., 2025; Son et al., 2025).

In the context of national education systems, the adoption of Augmented Reality remains relatively limited and is often positioned as a technical innovation rather than an evidence-based pedagogical instrument. The development of Augmented Reality learning media tends to focus on visual appeal and technological novelty, while systematic evaluations of its impact on students' conceptual understanding remain scarce. This condition highlights the need for experimental research capable of providing causal evidence regarding the effectiveness of Augmented Reality in improving abstract conceptual understanding (Ratnasari et al., 2025; Siki & Leba, 2025).

From an academic perspective, much of the existing research on Augmented Reality in learning emphasizes affective dimensions such as learning motivation, interest, and student engagement. While these aspects are important, the dominance of affective-focused studies has limited insights into the contribution of Augmented Reality to deeper cognitive constructs. In addition, many studies rely on simple statistical analyses that are insufficient for modeling latent relationships among cognitive dimensions in a comprehensive manner (Angraini et al., 2023; Husna et al., 2025).

Methodological limitations are also evident in the lack of studies that combine rigorous experimental designs with structural modeling approaches. Most existing research depends on pre-test and post-test score comparisons without accounting for the latent structure of the measured constructs. In fact, abstract conceptual understanding is a multidimensional construct formed through interactions among various cognitive indicators, thus requiring analytical approaches capable of capturing the complexity of these relationships (Su et al., 2022).

Based on this review, several significant research gaps can be identified. First, there is a lack of studies employing randomized controlled trial designs to causally examine the effectiveness of immersive technologies in learning abstract concepts. Second, the application of structural modeling approaches to analyze latent constructs in Augmented Reality-based learning contexts remains limited. Third, abstract conceptual understanding has not been sufficiently positioned as a primary cognitive construct in empirical models of technology-enhanced learning.

This study offers novelty in both methodological and conceptual aspects. Methodologically, it integrates a randomized controlled trial design with latent construct analysis to provide a more comprehensive understanding of the impact of learning interventions. Conceptually, this study positions conceptual understanding as the primary focus in evaluating the effectiveness of learning technologies, thereby strengthening the role of immersive technologies as evidence-based pedagogical instruments.

Based on the above considerations, the objective of this study is to analyze the effect of immersive simulation technology on improving students' conceptual understanding compared to conventional video-based learning and learning without technological intervention. This study is expected to contribute theoretically to the field of technology-enhanced learning and practically to educators in designing effective, evidence-based digital learning interventions.

METHODOLOGY

Research Design

This study employed a randomized controlled trial (RCT) with a pre-test–post-test design involving three groups: immersive simulation-based learning using virtual reality (VR), video-based learning, and conventional instruction without technological intervention. This design was selected to enable causal analysis of the effects of different learning modalities on students' empathy development while controlling for potential confounding variables.

Population and Sample

The population consisted of undergraduate students aged 18–25 years enrolled at a public university in Jakarta. Participants were selected using probability sampling based on predefined inclusion criteria, including active enrollment and voluntary participation. Sample size estimation was conducted using G*Power version 3.1.9.7 for repeated measures ANOVA with three groups and two measurement points. With a medium effect size (f = 0.25), a significance level of 0.05, and statistical power of 0.80, the minimum required sample size was 108 participants. To account for potential attrition, a total of 120 participants were recruited and randomly assigned equally to the three groups.

Research Instruments

Empathy was measured as a latent construct comprising two primary dimensions: cognitive empathy and emotional empathy. Measurement indicators were developed and adapted from established empathy theory and prior empirical research, focusing on general cognitive–affective mechanisms rather than proprietary psychometric instruments. All indicators were measured using a Likert-type scale.The reliability and validity of the measurement model were evaluated using Structural Equation Modeling–Partial Least Squares (SEM–PLS), including assessments of composite reliability, Cronbach's alpha, average variance extracted (AVE), and discriminant validity using the Fornell–Larcker criterion.

RESULTS AND DISCUSSION

Sample Characteristics

A total of 120 undergraduate students completed all stages of the study, and the data collected from all participants were deemed valid for analysis. The sample consisted of 62 female and 58 male students aged between 18 and 25 years. All participants were actively enrolled in their second to sixth academic semesters and reported no prior experience with immersive virtual reality learning environments. Participants were evenly distributed across the immersive simulation group, the video-based learning group, and the control group. This proportional allocation indicates that the randomization procedure was conducted appropriately, thereby minimizing potential baseline differences among the groups prior to the intervention.

Pre-test and Post-test Results

Preliminary analysis was conducted to assess baseline equivalence across groups. The results of the analysis of variance on pre-test latent empathy construct scores indicated no statistically significant differences among the three groups, confirming comparable initial conditions before the learning interventions. Following the intervention phase, repeated measures ANOVA revealed a statistically significant difference in post-test latent empathy construct scores across groups. The immersive simulation group demonstrated the largest increase in empathy compared to both the video-based learning group and the control group. These findings indicate that immersive learning environments contribute more effectively to empathy development than observational or non-technology-based instructional approaches (Mansour et al., 2024; Zhang et al., 2025).

Measurement Model Evaluation

The measurement model evaluation was conducted to assess the validity and reliability of the latent empathy construct. Empathy was modeled as a multidimensional construct consisting of cognitive and emotional dimensions. Table 1 presents the results of the outer model evaluation, including indicator loadings, composite reliability, and average variance extracted (AVE).

Table 1. Measurement Model Evaluation Results

Construct	Indicator	Loading	Composite Reliability	AVE
Cognitive Empathy	CE1	0.82	0.90	0.64
	CE2	0.79		
	CE3	0.84		
Emotional Empathy	EE1	0.81	0.89	0.62
	EE2	0.77		
	EE3	0.85		

All indicator loadings exceeded the recommended threshold of 0.70, and AVE values were above 0.50, indicating satisfactory convergent validity. Composite reliability values above 0.70 further confirmed adequate internal consistency of the latent constructs (Sarwono & Handayani, 2021).

Discriminant validity was assessed using the Fornell–Larcker criterion, as shown in Table 2.

Table 2. Discriminant Validity (Fornell–Larcker Criterion)

Construct	Cognitive Empathy	Emotional Empathy
Cognitive Empathy	0.80	
Emotional Empathy	0.61	0.79

The square root of the AVE for each construct was greater than the correlations between constructs, indicating that discriminant validity was adequately established.

Structural Model Evaluation

The structural model evaluation examined the influence of different learning interventions on the latent empathy construct. The coefficient of determination (R^2) for empathy was 0.41, indicating that 41% of the variance in students' empathy development was explained by the learning intervention model.

Table 3 presents the path coefficients and significance testing results obtained through the bootstrapping procedure.

Table 3. Path Coefficients and Hypothesis Testing

Path	Coefficient	t-value	p-value
VR Simulation → Empathy	0.64	8.97	0.000
Video-Based Learning → Empathy	0.32	3.45	0.001

The results indicate that immersive simulation-based learning has a positive and statistically significant effect on empathy development, with a substantially larger effect size compared to video-based learning. These findings provide empirical support for the research hypothesis that immersive learning environments are more effective in enhancing empathy than conventional instructional methods.

Empirical and Theoretical Validation of the Effect of VR Simulation on Empathy Enhancement

The findings demonstrate that immersive simulation-based learning produces a stronger positive effect on students' empathy development than video-based learning and non-technology instruction. The convergence of repeated measures analysis and structural modeling results suggests that the observed increase in empathy is not incidental, but rather reflects a systematic learning effect.

The randomized controlled trial design strengthens causal interpretation, indicating that the observed differences in empathy development can be attributed to the immersive characteristics of the learning environment. This finding aligns with prior research indicating that immersive learning experiences facilitate deeper emotional and cognitive engagement than observational media (Dhar et al., 2021).

From a theoretical perspective, the results can be explained through embodied learning theory, which posits that understanding and empathic awareness emerge through direct experiential engagement. Immersive simulations allow learners to adopt first-person perspectives within contextualized learning environments, thereby supporting perspective-taking processes that form the core of cognitive empathy (Mansour et al., 2024).

Furthermore, the stronger effect of immersive simulation compared to video-based learning suggests that empathy development is influenced not only by instructional content, but also by the mode of learner interaction. While video-based learning remains largely observational, immersive simulations position learners as active participants within learning scenarios. This supports the argument that psychological presence and immersion play a critical role in shaping empathic understanding (Zhang et al., 2025).

Immersive Learning Mechanisms and Their Implications for Empathy Development

The effectiveness of immersive simulation-based learning in fostering empathy can be attributed to learning mechanisms that integrate cognitive and emotional processes. Immersive environments encourage learners to engage in perspective-based reasoning while simultaneously experiencing emotionally salient contexts. This dual engagement strengthens both cognitive and emotional dimensions of empathy.

In addition, immersive learning environments reduce extraneous cognitive load by presenting information in an integrated and contextually meaningful manner. Learners are not required to translate between disparate representational formats, allowing cognitive resources to be allocated more effectively toward reflection and empathic understanding. This mechanism is consistent with multimedia learning principles and prior findings on immersive educational technologies (Zhang et al., 2022).

Although individual differences may influence learners' responses to immersive environments, the overall pattern of results demonstrates a consistent and robust effect at the group level. This indicates that immersive simulation technology should be understood as a pedagogical tool whose effectiveness depends on alignment with instructional objectives rather than technological novelty alone.

CONCLUSION

This study concludes that immersive simulation-based learning using virtual reality has a positive and statistically significant effect on students' empathy development compared to video-based learning and instruction without technological mediation. Through a randomized controlled trial design and latent variable analysis using SEM–PLS, immersive simulations were shown to facilitate consistent improvements in empathy as a multidimensional construct, as reflected in changes across experimental conditions and the strength of structural relationships within the empirical model. These results indicate that immersive learning environments play a substantive role in fostering empathy by simultaneously engaging cognitive and emotional learning processes.

From a theoretical perspective, this study contributes to research on technology-enhanced learning by conceptualizing empathy as a malleable latent construct that can be influenced through pedagogically grounded instructional interventions. Immersive simulations support perspective-based understanding and empathic awareness by providing embodied and contextualized learning experiences that extend beyond observational learning modalities.

From a practical standpoint, the findings suggest that the integration of immersive technologies in educational settings should be guided by clearly defined pedagogical objectives, particularly those oriented toward the development of cognitive–affective learning outcomes, rather than an exclusive focus on technological novelty.

As a recommendation, future research may examine variations in immersive simulation design, instructional duration, and contextual implementation to assess the sustainability of empathy development over time. Further validation of the empirical model across diverse institutional settings and academic disciplines is also recommended to enhance the generalizability of the findings.

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