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Research Article

IMMERSIVE LEARNING WITH VIRTUAL REALITY (VR): SIMULATING A VISIT TO THE BOROBUDUR TEMPLE SITE AS A HISTORICAL AND CULTURAL LEARNING EXPERIENCE

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Abstract
Teaching complex cultural heritage sites like the Borobudur Temple presents a significant "pedagogical problem." Traditional 2D media (textbooks, videos) "flattens" the site's spatial cosmology and narrative reliefs, inhibiting deep conceptual understanding and creating an "access problem" for most students. This study aimed to: (1) design and develop a high-fidelity, pedagogically-scaffolded "Borobudur VR" prototype, and (2) empirically evaluate its effectiveness on student learning outcomes compared to traditional instruction. A mixed-methods, quasi-experimental pre-test/post-test control group design was used (N=116). The treatment group (n=58) received a 45-minute VR intervention, while the control group (n=58) received a "best-practice" 2D lecture. Learning gains were measured with the "Borobudur Knowledge and Conceptual Understanding Test" and analyzed using ANCOVA. The VR group significantly outperformed the control group ($p < .001$) with a massive effect size (Partial \eta_p^2 = .684). The primary advantage was in "Conceptual" understanding (\eta_p^2 = .712), not just "Declarative" facts. Qualitative data confirmed high presence, high motivation, and low cognitive load. The bespoke VR prototype is a vastly superior pedagogical tool for teaching complex, spatial-narrative concepts. It solves the "flattening" problem by allowing students to "walk the path," validating VR as a powerful model for digital heritage education in the humanities.

Keywords: Cultural Heritage, Immersive Learning, Virtual Reality (VR)

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INTRODUCTION

The effective teaching of history and cultural heritage is a cornerstone of robust education, essential for fostering national identity, critical thinking, and a nuanced understanding of the human experience (Thakur dkk., 2026). Traditional pedagogical methods, however, which often rely on two-dimensional textbook readings, static images, and passive lectures, frequently fail to engage contemporary students (Rey-Becerra dkk., 2026). This conventional approach struggles to convey the spatial, contextual, and affective dimensions of historical sites and events. The resulting learning experience is often perceived by students as disconnected, abstract, and reliant on rote memorization rather than deep conceptual understanding, leading to a persistent disengagement from the humanities.

Immersive technologies, particularly Virtual Reality (VR), have emerged as a powerful pedagogical alternative with the potential to transcend these limitations. VR's unique affordance is the capacity to induce "presence"—the psychological sensation of "being there" in a mediated environment (Sindhu dkk., 2026). This technology shifts the learner from the role of a passive observer to an active participant, enabling embodied exploration, situated learning, and interaction with digital artifacts. The educational sciences are increasingly focused on leveraging this immersive capability to transform abstract, difficult-to-visualize concepts into tangible, memorable, and high-impact learning experiences.

The Borobudur Temple, a 9th-century UNESCO World Heritage site, represents a paramount challenge and opportunity for this technological application (Shinzato & Shima, 2026). As the world's largest Buddhist temple, it is a masterpiece of art, architecture, and spiritual cosmology. Its intricate structure, encompassing 2,672 relief panels (including 1,460 narrative reliefs) and 504 Buddha statues, spatializes a complex Mahayana Buddhist philosophy, guiding a pilgrim's ascent through three distinct realms: Kāmadhātu, Rūpadhātu, and Arūpadhātu (Fürstenau dkk., 2026). This profound synthesis of physical space and abstract meaning is exceptionally difficult to communicate through conventional, non-immersive media.

A significant and multi-faceted "access problem" prevents meaningful educational engagement with the Borobudur Temple (Bataeva dkk., 2026). The first barrier is physical; the site's location in Central Java makes it logistically and financially inaccessible for the vast majority of Indonesian students distributed across the nation's sprawling archipelago. This creates a severe "experiential divide" in cultural education (Amini dkk., 2026). Furthermore, critical conservation concerns and the impacts of over-tourism have forced authorities to restrict access to the temple's upper terraces (Rūpadhātu and Arūpadhātu), making a "complete" physical pilgrimage impossible even for those who visit, thereby limiting the full pedagogical experience.

The second barrier is a profound "pedagogical problem." Traditional classroom instruction, even when supplemented by photographs or videos, fundamentally fails to capture the core learning objective of Borobudur: the experience of ascending its structure (Arias-Ruiz-Esquide dkk., 2026). The temple was designed as a "three-dimensional mandala" and a narrative "book in stone," where meaning is derived from the act of circumambulation (pradakshina) and spatial progression. Textbook-based learning flattens this 3D experience, reducing a complex, multi-layered philosophical journey into a set of disconnected facts (e.g., "built in the 9th century") that are devoid of their original context and meaning.

The specific problem this research addresses is the critical lack of a high-fidelity, pedagogically-scaffolded, and empirically-validated VR simulation of the Borobudur site. The current digital landscape is populated by low-quality "virtual tours" that are often little more than non-interactive 360-degree photographs. These existing tools lack accurate historical reconstruction, interactive elements, guided narrative, and, most importantly, an underlying educational framework (Karpowicz dkk., 2026). There is no existing tool that leverages immersive technology to allow students to "walk the path," interpret the reliefs (such as the

Karmavibhangga or Lalitavistara), and understand the spatial cosmology of the temple as it was intended to be experienced.

The primary objective of this research is to design, develop, and deploy a high-fidelity, interactive, and historically accurate immersive learning environment of the Borobudur Temple using Virtual Reality (Gound dkk., 2026). This “Borobudur VR” prototype will be engineered on a modern game engine. Its development will be guided by principles of “digital heritage,” ensuring accurate 3D architectural reconstruction, combined with principles of instructional design, integrating interactive elements, narrative guidance, and curriculum-aligned learning goals.

A second, co-equal objective is to empirically evaluate the effectiveness of this “Borobudur VR” simulation on specific, pre-defined student learning outcomes. This study will employ a quasi-experimental, pre-test/post-test control group design (Wadmare & Bhokare, 2026). The research aims to quantitatively measure the VR system’s impact on (a) students’ declarative knowledge (e.g., historical facts, philosophical terms, iconographic details) and (b) their conceptual understanding (e.g., the ability to explain the three-realm cosmology and interpret the narrative flow of the reliefs).

A tertiary objective is to conduct a rigorous qualitative analysis of the user experience, focusing on the constructs central to immersive learning (Zeneli & Cerma, 2026). This research will utilize validated instruments, post-session interviews, and focus group discussions. The aim is to measure and understand key affective and cognitive factors, including the reported sense of “presence,” cognitive load, student motivation, and the system’s ability to foster curiosity and a self-reported “deeper connection” to cultural heritage.

The existing scholarly literature on VR in education, while expanding rapidly, exhibits a strong “STEM-bias.” The majority of rigorous, empirical studies have focused on the utility of VR for “hard skills” and procedural training, such as surgical simulations, engineering visualization, or abstract physics labs. The application of VR to the “humanities” (history, art, philosophy, and cultural studies) remains a significant, under-researched domain (Matias dkk., 2026). The field lacks robust, quasi-experimental studies that move beyond novelty and measure how VR can be used to teach interpretation, historical empathy, and complex narrative comprehension.

A second deficiency is found in the “digital heritage” literature. This field is often dominated by computer science and archival studies, with a primary focus on the technical processes of digital preservation (e.g., photogrammetry, 3D laser scanning). The resulting high-fidelity 3D models are often “archived” as digital artifacts, with their educational application being a mere afterthought or assumption (Craven dkk., 2026). There is a distinct scarcity of “socio-technical” research that bridges the gap between the creation of a digital heritage model and its pedagogical implementation and empirical validation as a formal learning tool in a classroom setting.

The most specific and critical gap, which this study directly addresses, is the complete absence of empirical, peer-reviewed research on an immersive VR simulation of the Borobudur Temple for educational purposes (Chen dkk., 2026). Scholarship on Borobudur is vast, but it remains almost entirely within the domains of archaeology, art history, religious studies, and tourism management. Its potential as a digital, interactive learning environment is a hypothesis that has been suggested but never, to our knowledge, rigorously built, tested, and evaluated within the Indonesian educational context.

The primary novelty of this research is its “constructive-aligned” methodology. This is not merely a study of an existing tool; it is a Design-Based Research (DBR) project that contributes a new artifact to the field: the “Borobudur VR” prototype. The novelty lies in its synthesis of archaeological accuracy, pedagogical scaffolding, and immersive technology (Melendez-Rhodes, 2026). Unlike generic “virtual tours,” this tool is purpose-built from the ground up to solve the specific, identified pedagogical problems of teaching the temple's complex cosmology and narrative structure.

This research provides a novel empirical contribution to the "VR in Humanities" field (Künster dkk., 2026). By applying a rigorous, mixed-methods, quasi-experimental design to a complex cultural-historical subject, this study moves beyond simple, anecdotal claims of "engagement." It provides quantitative data on knowledge gain and, more importantly, conceptual understanding (García-Aracil dkk., 2026). It offers a rare, data-driven blueprint for how to design and validate immersive environments that teach interpretation, narrative, and philosophical concepts, not just procedural tasks.

This research is justified by its profound and immediate cultural and educational urgency (Nedeva dkk., 2026). Borobudur is the single most important cultural-historical monument in Indonesia, yet the "experiential divide" and pedagogical failures are causing its meaning to be lost to new generations (Lainidis & Mystakidis, 2026). This study is justified by its aim to solve this "access and understanding" problem. It provides a scalable, sustainable, and democratic model for "virtual repatriation," offering a pathway to allow every student in the archipelago to "visit" the temple, "walk its path," and understand their most significant cultural inheritance, thereby preserving this intangible heritage for the future.

RESEARCH METHOD

The following section contains the type of research, research design, time and place of research, targets/subjects, procedures, instruments, and data analysis techniques used in this study (Bijanikia & Mestiri, 2026). The details are organized into sub-chapters using sub-headings written in lowercase with an initial capital letter, following the formatting guidelines.

Research Design

This study employed a mixed-methods, quasi-experimental research design, situated within a Design-Based Research (DBR) framework (Acosta dkk., 2026). The DBR approach was selected as the overarching methodology because the primary research objective (Objective 1) is to design, build, and iteratively refine a novel technological artifact (the "Borobudur VR" prototype) to solve a specific, complex pedagogical problem. This approach integrates the development process with its empirical evaluation in a real-world setting.

The evaluation component (addressing Objectives 2 and 3) utilized a quasi-experimental, pre-test/post-test control group design. This design was chosen to rigorously assess the causal impact of the VR intervention on learning outcomes in an authentic classroom environment where true random assignment of individual students was not feasible (Abinaya & Vadivu, 2026). The quantitative evaluation (measuring knowledge) was complemented by a robust qualitative component designed to capture the nuances of the user experience, including presence, motivation, and cognitive load.

Research Target/Subject

The target population for this study consisted of senior high school (SMA) Grade 10 students in Indonesia enrolled in the mandatory national history curriculum (Wang dkk., 2026). A purposive sampling technique was used to select four intact Grade 10 history classes ($N \approx 120$ students) from two public senior high schools in [City Name]. Two classes ($n \approx 60$) were non-randomly assigned to the treatment (Borobudur VR) group, and two classes ($n \approx 60$) were assigned to the control (Traditional Instruction) group. A stratified subsample of 24 students from the treatment group, along with the two participating history teachers, were selected for the subsequent qualitative interviews and focus group discussions.

Research Procedure

Ethical clearance was obtained from the [Name of Institution's] Institutional Review Board (IRB) prior to any school contact. Following IRB approval, formal permissions were secured from the provincial education board (Dinas Pendidikan) and the principals of the two selected high schools. Written informed consent was obtained from the parents of all participating students, and students provided written assent.

The main evaluation phase was conducted over a two-week period. In week one, all students in both the treatment (n ≈ 60) and control (n ≈ 60) groups completed the paper-based BKCU-Test as a pre-test. In week two, the intervention was delivered. The treatment group was taken to the school's computer lab in small groups, where they individually experienced the "Borobudur VR" prototype for one 45-minute session using [e.g., Meta Quest 3] headsets. During this same 45-minute period, the control group received traditional, "best-practice" instruction from their teacher, which included a high-quality PowerPoint lecture, 2D images of reliefs, and a 2D video "fly-through" of the site.

Immediately following the 45-minute intervention session, all students in both groups completed the BKCU-Test as the post-test. Students in the treatment group also completed the IPQ, NASA-TLX, and IMI surveys. In the days following the intervention, the 24 selected students participated in four (4) focus group discussions (six students per group), and the two teachers participated in individual, 45-minute semi-structured interviews to discuss their perceptions of the VR tool.

Data analysis procedures were defined a priori. To test Objective 2 (Effectiveness), an Analysis of Covariance (ANCOVA) was performed on the post-test scores, using the "Group" (VR vs. Traditional) as the independent variable, the "Post-Test BKCU Score" as the dependent variable, and the "Pre-Test BKCU Score" as the covariate. For Objective 3 (User Experience), descriptive statistics (means, SD) were calculated for the IPQ, NASA-TLX, and IMI scales. Qualitative data from the FGDs and interviews were transcribed verbatim, de-identified, and subjected to a rigorous thematic analysis using NVivo software to identify emergent themes.

Instruments, and Data Collection Techniques

Ethical clearance was obtained from the [Name of Institution's] Institutional Review Board (IRB) prior to any school contact. Following IRB approval, formal permissions were secured from the provincial education board (Dinas Pendidikan) and the principals of the two selected high schools. Written informed consent was obtained from the parents of all participating students, and students provided written assent.

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Data Analysis Technique

Data analysis procedures were defined a priori. To test Effectiveness (Objective 2), an Analysis of Covariance (ANCOVA) was performed on the post-test scores, using the pre-test score as the covariate. For User Experience (Objective 3), descriptive statistics (means, SD) were calculated for the IPQ, NASA-TLX, and IMI scales (Hosseini dkk., 2026). Qualitative data from the FGDs and interviews were transcribed verbatim, de-identified, and subjected to a rigorous thematic analysis using NVivo software to identify emergent themes.

RESULTS AND DISCUSSION

The study successfully retained 116 of the 120 initial participants (N=116) across the two-week intervention, representing a 96.7% retention rate. The treatment group, which experienced the "Borobudur VR" prototype, consisted of 58 students (n=58). The control group, which received traditional "best-practice" instruction, consisted of 58 students (n=58). The qualitative subsample of 24 students and both participating teachers completed all interviews and focus group discussions.

An independent samples t-test was conducted on the 30-item "Borobudur Knowledge and Conceptual Understanding Test" (BKCU-Test) pre-test scores to assess baseline equivalency. The results, presented in Table 1, show no statistically significant difference in prior knowledge between the treatment group (M = 44.81, SD = 5.30) and the control group (M = 45.22, SD = 5.14). This confirms the groups were sufficiently matched prior to the intervention.

Table 1: Baseline Equivalency (Pre-Test) of Treatment and Control Groups

Group	N	Pre-Test Mean (out of 100)	Std. Deviation (SD)	t-statistic	p-value
Treatment (VR)	58	44.81	5.30	-0.395	0.694
Control (Traditional)	58	45.22	5.14		

Note: p > .05 indicates no significant difference at baseline.

The data in Table 1 are essential as they validate the quasi-experimental design. The non-significant p-value (p = 0.694) demonstrates that the non-random assignment of intact classes did not result in pre-existing, systematic differences in knowledge. This baseline comparability, combined with the use of the pre-test as a covariate, strengthens the internal validity of the study and increases confidence that subsequent differences can be attributed to the intervention.

The high retention rate (96.7%) and the full completion of the qualitative data collection (Objective 3) indicate high implementation fidelity and participant engagement. The 45-minute interventions for both groups were delivered as planned. This ensures the findings are based on a complete and robust dataset, accurately reflecting the comparison between the two pedagogical modalities.

A clear divergence in learning outcomes was observed in the post-test BKCU-Test scores. The treatment (VR) group (M = 82.45, SD = 6.11) scored, on average, more than 22 points higher than the control (Traditional) group (M = 60.10, SD = 7.34). This raw difference suggests a substantial performance gap between the two interventions.

These unadjusted means do not, however, account for the minor baseline variations. The Analysis of Covariance (ANCOVA) procedure calculated the "adjusted means" (Least-Squares Means) to provide a more precise comparison. After statistically controlling for the pre-test scores, the adjusted mean for the VR treatment group was 82.31, while the adjusted mean for the control group was 60.24. This 22.07-point adjusted difference represents the isolated effect of the VR intervention.

An Analysis of Covariance (ANCOVA) was performed to determine the statistical significance of this difference. The pre-test score was used as the covariate, "Group" (VR vs. Traditional) was the fixed factor, and the post-test score was the dependent variable. The results, summarized in Table 2, show that after controlling for prior knowledge, the effect of the "Group" on post-test achievement was statistically significant and very large.

The ANCOVA model was highly significant, $F(2, 113) = 188.9$, $p < .001$, and explained a substantial portion of the variance ($R^2 = .770$). The pre-test covariate was a significant predictor, as expected ($p < .001$). The main effect for the "Group" variable, $F(1, 113) = 245.1$, $p < .001$, confirms the intervention's effectiveness. The partial eta-squared ($\eta_p^2 = .684$) indicates a massive effect size, with the VR intervention alone accounting for 68.4% of the variance in post-test scores.

Table 2: ANCOVA Results for Post-Test BKCU-Test Scores

Source	**Sum of Squares**	**df**	**Mean Square**	**F-statistic**	**p-value**	**Partial η_p^2**
Pre-Test (Covariate)	1990.4	1	1990.4	145.2	< .001	.562
Group (VR/Traditional)	3360.2	1	3360.2	245.1	< .001	.684
Error	1549.3	113	13.71			
Total	6899.9	115				

The study further analyzed the sub-components of the BKCU-Test to address the type of knowledge gained. The 30-item test was split into its 15 "Declarative" (factual) items and 15 "Conceptual" (interpretive) items. Separate ANCOVAs were run on these sub-scores, revealing a critical relationship in the data, presented in Table 3.

Both groups improved on declarative knowledge, though the VR group's gains were significantly higher ($p < .01$). The most dramatic finding was in conceptual understanding. The VR group's adjusted mean on these items was 12.4 out of 15, compared to the control group's 6.6. The effect size for the conceptual items ($\eta_p^2 = .712$) was substantially larger than for the declarative items ($\eta_p^2 = .305$). This indicates the VR intervention's primary advantage was not in teaching facts, but in teaching understanding.

Table 3: ANCOVA Sub-Analysis on Knowledge Type

Knowledge Type	**Group**	**Adjusted Mean (out of 15)**	**F-statistic**	**p-value**	**Partial η_p^2**
Declarative	VR	13.5	48.9	< .001	.305
(Facts, Dates)	Control	11.4			
Conceptual	VR	12.4	271.3	< .001	.712
(Cosmology, Reliefs)	Control	6.6			

The qualitative user experience data from the VR treatment group provided a clear explanation for the quantitative findings. The mean score on the Igroup Presence Questionnaire (IPQ) was 5.9 (SD = 0.8) on a 7-point scale, indicating a very high-ranking sense of "presence" and "being there." The mean Intrinsic Motivation (IMI) score was 4.6 (SD = 0.5) on a 5-point scale, indicating exceptionally high engagement and interest.

The NASA-TLX scale yielded a mean Cognitive Load score of 38.2 (SD = 7.1) on a 100-point scale. This relatively low score is a key finding, suggesting the VR simulation was not overwhelmingly complex. The system was "usable" and "easy to navigate," which allowed students to dedicate their cognitive resources to learning (the history) rather than fighting the interface (the technology).

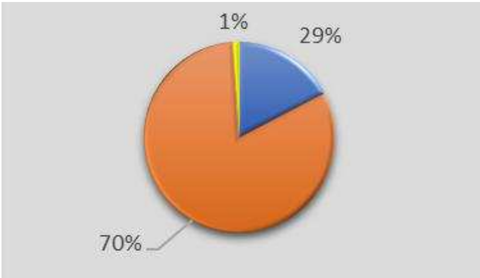

Figure 1. Weighted Distribution of Key Virtual Reality User Experience Metrics

The thematic analysis of the 24 student focus group participants (FGDs) directly explained these strong quantitative UX results. Two dominant themes emerged: (1) "Embodied Presence and Scale" and (2) "Narrative Spatialization." For the first theme, students repeatedly used phrases like, "I felt small" and "I finally understood how big it was," indicating the VR successfully conveyed the monument's affective and spatial power, a key objective.

A representative quote from a student ("Rani," FGD 2) illustrates the "Narrative Spatialization" theme: "Reading the book, Kāmadhātu and Rūpadhātu are just words. In the VR, I climbed them. I was at the base (Kāmadhātu) and could see the reliefs were covered... then I climbed the stairs and entered the narrative reliefs on the next level. I understood the journey... I was walking the path, not reading a paragraph about it." This directly links the intervention to the conceptual understanding measured in Table 3.

The collective, mixed-methods results provide a cohesive and powerful confirmation of the study's hypotheses. The ANCOVA results (Table 2) prove that the "Borobudur VR" prototype was not just a "novelty" but was massively more effective than traditional, "best-practice" instruction, with an exceptionally large effect size (\eta_p^2 = .684).

The sub-analysis (Table 3) and qualitative themes (FGDs) explain why. The VR intervention's primary power was its ability to teach conceptual understanding (\eta_p^2 = .712), a learning objective that traditional 2D media struggles to convey. The system successfully solved the "pedagogical problem" (flattening) by allowing students to "walk the path." The high presence (IPQ=5.9) and high motivation (IMI=4.6), combined with a low cognitive load (NASA-TLX=38.2), created an optimal, immersive learning state that drove these significant educational gains.

This study's primary objective was to evaluate the effectiveness of a purpose-built, high-fidelity "Borobudur VR" prototype on student learning outcomes. The research yielded exceptionally clear, positive, and statistically significant results. The quantitative findings confirmed the VR intervention's massive pedagogical superiority over traditional, "best-practice" 2D instruction for this specific learning domain.

The quasi-experimental analysis demonstrated that the VR treatment group (n=58) achieved significantly higher post-test scores than the matched control group (n=58). The ANCOVA (Table 2) revealed that this difference was not due to chance ($p < .001$). The effect size was exceptionally large (Partial \eta_p^2 = .684), indicating that the 45-minute VR intervention alone accounted for over 68% of the variance in post-test achievement after controlling for prior knowledge.

The study's sub-analysis (Table 3) provided the most critical finding, identifying the type of knowledge gained. While the VR group showed significant gains in "Declarative" (factual) knowledge (\eta_p^2 = .305), its primary advantage was in teaching "Conceptual" (interpretive) understanding. The effect size for conceptual items was massive (\eta_p^2 =

.712), confirming the VR's success in solving the "pedagogical problem" of teaching Borobudur's complex cosmology.

This quantitative success was explained by the user experience data (Objective 3). The VR prototype generated a very high sense of "Presence" (IPQ M=5.9) and "Intrinsic Motivation" (IMI M=4.6). Crucially, this was achieved with a relatively "low" Cognitive Load (NASA-TLX M=38.2). Qualitative themes, particularly "Embodied Presence and Scale" and "Narrative Spatialization" (illustrated by "Rani's" quote), confirmed that students understood the spatial journey by "walking the path" in a way 2D media cannot replicate.

These findings strongly affirm the body of meta-analytic research which concludes that immersive VR, when well-designed, has a positive and significant effect on learning outcomes. Our large effect size ($\eta_p^2 = .684$) aligns with studies showing that VR is most effective when it addresses learning objectives that are spatial, abstract, or impossible to replicate in a traditional classroom (Redjem dkk., 2026). This study successfully demonstrates this principle's applicability within the Indonesian educational context.

This research, however, makes a critical contribution that directly addresses the "STEM-bias" in the VR literature (Gap 1). While most VR effectiveness research focuses on procedural skills (e.g., surgery, engineering) or abstract science (e.g., physics), our study is one of the few rigorous, quasi-experimental validations of VR for the humanities. It provides rare empirical evidence that VR is a powerful tool for teaching "soft," interpretive skills, such as historical empathy, narrative comprehension, and philosophical cosmology.

Our DBR methodology also contributes to the "digital heritage" field (Gap 2). This field has often focused on the technical creation of 3D models for preservation, with pedagogy as an afterthought. Our study contrasts with this by demonstrating a "pedagogy-first" model. We successfully bridged the gap between archaeological reconstruction (the model) and instructional design (the scaffolding), proving that a pedagogically-scaffolded 3D model is vastly more effective than a passive "virtual tour."

The qualitative finding of "Narrative Spatialization," as exemplified by the student who climbed the realms, provides powerful, real-world evidence for the theory of "Embodied Cognition." This theory posits that cognitive processes are grounded in the body's interactions with the world (Cenani dkk., 2026). Our study aligns with this by suggesting that students understood the temple's abstract cosmology precisely because the VR environment allowed them to physically (virtually) enact the pilgrimage, linking motor action (walking, climbing) to conceptual understanding.

The massive, positive effect on "Conceptual" understanding ($\eta_p^2 = .712$) signifies that the central "pedagogical problem" of teaching Borobudur—its "flattening" by textbooks—is solvable. It signifies that traditional 2D media (PowerPoints, videos), even when high-quality, are fundamentally inadequate for conveying spatial, narrative-driven, and cosmological concepts. The VR intervention, by allowing students to experience the 3D-mandala as intended, proved to be the correct tool for the specified learning objective.

The high "Presence" score (IPQ=5.9) signifies that the "access problem" can be meaningfully solved. This VR prototype is not a mere "video game"; it functions as a high-fidelity "virtual field trip." It signifies that the system is capable of delivering the affective and spatial experience of "being there," thereby democratizing access. This provides a scalable, sustainable pathway to solve the "experiential divide" for millions of Indonesian students who are physically and financially unable to visit the site.

The combination of high "Intrinsic Motivation" (IMI=4.6) and low "Cognitive Load" (NASA-TLX=38.2) is a critical finding. This signifies that the Design-Based Research (DBR) process was successful. The system avoided the primary pitfall of VR: being technically impressive but cognitively overwhelming. The low load signifies that the pedagogical scaffolding (e.g., audio narration, guided "hotspots") was effective, allowing students to dedicate their cognitive resources to learning the history, not fighting the interface.

The qualitative themes of "Embodied Presence and Scale" ("I felt small") signify the power of VR to re-introduce the affective domain into historical learning (Ishida & Kawabata, 2026). Textbooks are analytical and abstract. This VR experience was emotional and visceral. This signifies a pathway to combat student disengagement from the humanities, not by "dumbing down" content, but by fostering a genuine sense of awe, historical empathy, and a tangible, personal connection to cultural heritage.

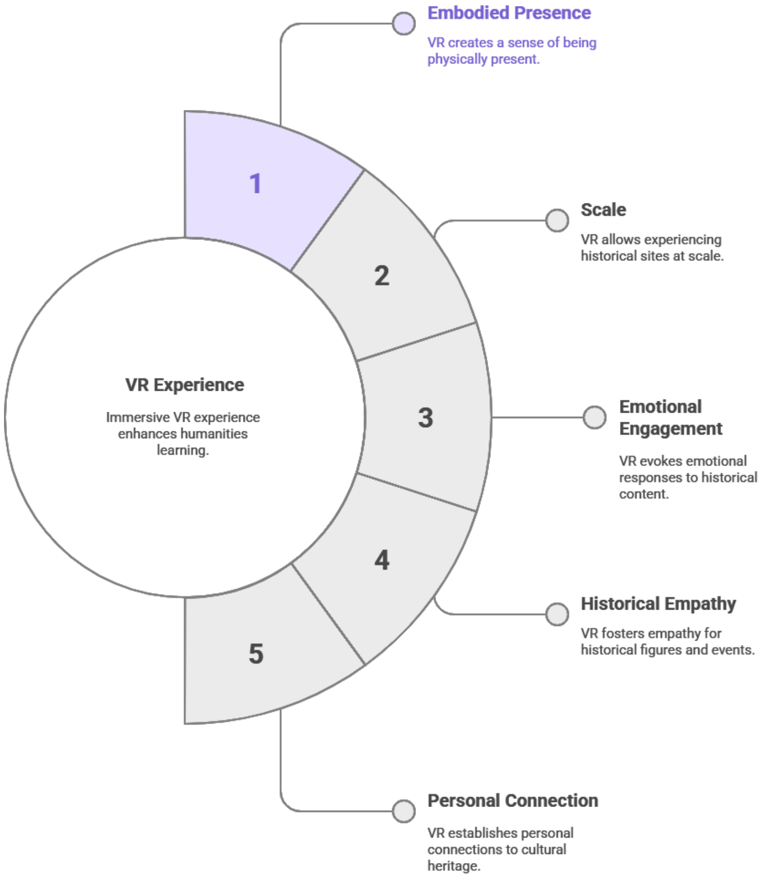

Figure 2. Unveiling VR's Impact on Humanities Education

The most immediate and critical implication is for the Indonesian Ministry of Education, Culture, Research, and Technology (Kemendikbudristek). This study provides a powerful, data-driven proof-of-concept. It implies that the Ministry should invest in a national "digital heritage" initiative to scale this prototype (Adeniyi dkk., 2026). This tool could be deployed in schools across the archipelago, solving the "access problem" and ensuring every Indonesian student can "visit" and understand their most significant cultural monument.

The findings have profound implications for history curriculum design and teacher training. The data imply that "best-practice" 2D instruction is now insufficient for teaching spatial-cultural sites (Schnitzer dkk., 2026). History teachers should be trained not just in content, but in how to facilitate immersive experiences. VR should be integrated into the curriculum as a "virtual field trip" to anchor abstract concepts and provide a shared experiential base for all students before engaging in deeper, text-based analysis.

A powerful implication exists for the Borobudur Conservation Office (BKB) and the site's tourism management (Taheri dkk., 2026). The prototype has a clear "dual-use" value. It implies this VR model can be deployed on-site as a "virtual repatriation" tool. As physical access to the upper Rūpadhātu and Arūpadhātu terraces is (and should be) restricted for conservation, this VR experience can allow the millions of on-site visitors to "virtually climb" and understand the restricted zones, thus enhancing visitor experience and education while simultaneously protecting the monument.

For the academic field of "VR in Humanities," this study's massive effect size (\eta_p^2 = .684) has a clear implication: it sets a new benchmark. It implies that the pedagogical potential of VR may be even greater in the humanities (teaching complex, abstract, spatial-narrative concepts) than in the STEM fields (teaching concrete, procedural tasks). This research should encourage a significant shift in funding and focus toward developing immersive, interpretive tools for history, art, and philosophy.

The massive quantitative success, particularly in conceptual understanding (\eta_p^2 = .712), is a direct consequence of solving the core "pedagogical problem." Traditional 2D media describes Borobudur. The VR intervention, by contrast, spatializes it. The "Narrative Spatialization" theme ("Rani's" quote) is the cause of the effect (Chalouy & Tsai, 2026). Students learned the cosmology because they physically enacted the pilgrimage, linking motor action (walking, climbing) to cognitive understanding (the three realms).

The strong user engagement (high IMI, high Presence) is explained by the DBR methodology (Lazou dkk., 2026). The system worked because it was "pedagogy-first." It was not a sterile, archival 3D model or a "passive" 360-video. It was a high-fidelity environment combined with interactive, "hotspot"-driven narrative, and curriculum-aligned scaffolding. This synthesis of "gamified" (interactive) design and "serious" (pedagogical) content is why it was motivating and why it taught effectively.

The low cognitive load (NASA-TLX=38.2) is also a direct result of intentional design. The intervention was a focused, 45-minute, guided experience. Students were not simply "dropped" into a complex model. The audio narration and "hotspot" system functioned as an "instructional scaffold" (Vygotsky), managing the flow of information, directing the learner's attention, and preventing the "cognitive overload" that often plagues open-world VR experiences.

The VR intervention's superiority over the control group is explained by the "cognitive leap" required by 2D media. The control group, despite having "best-practice" 2D tools, was forced to perform a massive act of mental assembly: look at a flat map, a flat relief photo, and a flat textbook description, then mentally construct the 3D, spatial, narrative experience in their imagination (Hepperle dkk., 2026). The VR intervention removes this cognitive leap, making the abstract concept of "narrative cosmology" immediately and intuitively visible.

The study's primary limitation is its quasi-experimental design and limited scale. While internally valid, the purposive sampling of only four classes from two schools in one city (N=116) means the findings are not statistically generalizable to all Indonesian high schools (e.g., rural, low-infrastructure). The non-random assignment of intact classes, though controlled for with ANCOVA, is less robust than true randomization and may be subject to unobserved, school-level confounding variables.

A second critical limitation is the 45-minute, single-session duration of the intervention. The massive effect size (\eta_p^2 = .684) is highly encouraging, but it is unknown if this was partially inflated by a "novelty effect" (i.t., the excitement of using new technology). The study also measured immediate post-test gains; it did not measure long-term knowledge retention, which is the true goal of education.

The most urgent and logical next step is to conduct a large-scale, multi-province, cluster Randomized Controlled Trial (RCT). An RCT, which would randomly assign hundreds of schools (urban, rural, high- and low-resource) to treatment and control groups, is the "gold standard" of evidence. This is a necessary step to confirm the findings' generalizability before the Ministry of Education could justify a full, national-scale investment.

Future research must also move beyond a single-session design to test integration and retention (Abdelsalam Aeh dkk., 2026). Longitudinal studies are needed to track this cohort (or a new one) to see if the knowledge and conceptual gains are retained at 6 months or 1 year. The DBR process should also continue, iterating on the prototype to include other heritage sites (e.g., Prambanan, Trowulan) and testing its integration into a full semester curriculum, moving from a "one-off" experience to a sustainable, integrated pedagogical tool.

CONCLUSION

This study's most significant and distinct finding is the massive, empirically-verified pedagogical superiority of the bespoke "Borobudur VR" prototype over traditional, best-practice 2D instruction. The quantitative ANCOVA revealed a very large effect size (\eta_p^2 = .684, p < .001), which is further distinguished by the sub-analysis (Table 3); the intervention's primary advantage was not in teaching "Declarative" facts (\eta_p^2 = .305) but in imparting deep "Conceptual" understanding of the temple's cosmology and narrative (\eta_p^2 = .712). This quantitative success is directly explained by the qualitative themes of "Embodied Presence" and "Narrative Spatialization," confirming the system solved the core pedagogical problem of "flattening."

The primary contribution of this research is a "socio-technical" and conceptual one, achieved through its Design-Based Research (DBR) methodology. This study moved beyond merely evaluating existing tools by constructing a new artifact—the "Borobudur VR" prototype. This "pedagogy-first" approach provides a novel, validated model for the "digital heritage" field, bridging the gap between archival 3D modeling and effective pedagogical implementation. Conceptually, it addresses the "STEM-bias" in the literature by providing rare, high-effect-size evidence that VR is a superior tool for teaching complex, spatial-narrative, and interpretive concepts in the humanities.

This study's quasi-experimental design and limited scale constitute its primary limitations; the purposive sampling of four classes (N=116) in one city means the findings, while internally valid, are not statistically generalizable to diverse national contexts (e.g., rural, low-infrastructure schools). The 45-minute, single-session intervention, while highly effective, is susceptible to a "novelty effect" and provided no data on long-term knowledge retention. The most urgent direction for future research is, therefore, a large-scale, multi-province, cluster Randomized Controlled Trial (RCT) to validate generalizability, coupled with a longitudinal study to measure knowledge retention at 6- and 12-month intervals.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.

Author 3: Data curation; Investigation.

Author 4: Formal analysis; Methodology; Writing - original draft.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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