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Effectiveness of the CERIA Flipbook on Elementary Students' Disaster Literacy and Conceptual Understanding: A Research and Development Study

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Abstract

Elementary science learning on volcanic eruption topics remains challenging for students. This difficulty arises from the abstract nature of the content and the limited use of interactive visual media, which often leads to low conceptual understanding. This study aims to develop and evaluate the CERIA flipbook (Creative Education with Augmented Reality for Science) as an AR-based learning medium that integrates contextual elements from students' daily environments to support meaningful learning. The study employed a Research and Development (R&D) approach using the ADDIE model and implemented a one-group pretest–posttest design involving 25 fifth-grade students at SD Negeri Kodasari I, Majalengka, Indonesia. Data were collected through expert validation sheets, essay-based pretest and posttest, and student response questionnaires, and were analyzed using descriptive, quantitative, and inferential techniques. The results indicate that the media is highly feasible, with validation scores of 90.83% from media experts and 94.44% from content experts. Students' conceptual understanding improved significantly, as reflected in the increase of mean scores from 41.8 to 82.64 ($p < 0.001$), with an N-Gain score of 0.73, categorized as high. In addition, students showed very positive responses toward the media, with an average score of 91.25%. These findings contribute to the growing evidence on the integration of contextual elements into AR-based science learning and offer a replicable pedagogical model for enhancing disaster literacy in elementary education.

Keywords: *Augmented Reality, Conceptual understanding, Localised learning context*

A. Introduction

Science education at the elementary level plays a fundamental role in shaping young learners' understanding of natural phenomena, yet topics such as volcanic eruptions present unique instructional challenges due to their abstract and unobservable nature. Concepts including magma generation, subsurface pressure accumulation, and eruption mechanisms require learners to mentally visualize processes that occur deep within the Earth's crust—far beyond direct sensory experience. According to Piaget's theory of cognitive development, elementary school children are in the concrete operational stage, where meaningful learning occurs through direct, tangible, and observable experiences (Piaget, 1972). When abstract scientific concepts are introduced without concrete mediation, students frequently develop misconceptions or an incomplete understanding. A systematic review of mobile augmented reality (AR) applications in geography education confirms that AR enhances understanding of invisible structures and processes, yet its application in disaster-vulnerable regions remains limited (2025). This cognitive-pedagogical tension is not merely an academic concern; in disaster-prone nations such as Indonesia—home to over 120 active volcanoes—the failure to

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comprehend volcanic processes directly compromises disaster literacy and community resilience.

The urgency of addressing this issue is particularly acute in regions such as Majalengka, West Java, where SD Negeri Kodasari I is located in proximity to Mount Ciremai, an active volcano. Previous research on Mount Ciremai has identified significant disaster risk levels in the surrounding areas, necessitating educational interventions that integrate disaster literacy into the curriculum (Firmansyah et al., 2015). Despite this geographical reality, science instruction in Indonesian elementary schools remains predominantly teacher-centered, relying on textbooks, static illustrations, and lecture-based methods. A preliminary exploration of digital media in Indonesian elementary science education found that teaching heavily relies on lectures and textbook illustrations, with minimal integration of interactive or visual media (Muslimasari et al., 2025). This pedagogical approach limits students' opportunities to actively engage with course material or visualize dynamic geological processes. Consequently, students' conceptual understanding of volcanism remains less than optimal, with passive learning environments hindering the development of causal reasoning—a core component of scientific literacy. The integration of digital flipbooks has been shown to increase student engagement, strengthen reading comprehension, and spark interest in scientific literacy (Rahmadhani et al., 2025). Thus, a significant disconnect exists between the concrete operational learning needs of elementary students and the predominantly abstract, text-based instruction they receive.

To address these instructional challenges, Augmented Reality (AR) has emerged as a promising educational technology. Recent studies demonstrate that AR-based interventions significantly enhance student engagement, motivation, and conceptual understanding in geoscience education by enabling interactive three-dimensional visualization of abstract concepts. For instance, the Augmented Reality Atlas Volcano Series (ARAVS) improved students' understanding of volcanic structures and eruption sequences, with students reporting that the AR media was "concrete, innovative, and interactive" (Prasetya et al., 2024, p. 3133). Similarly, AR-based flipbook media has been developed to improve learning outcomes in elementary science, showing significant increases in student comprehension (Silmi & Bektiningsih, 2025). However, a rigorous analysis of existing literature reveals four critical gaps. First (empirical gap) , most studies measure levels of knowledge gain but do not explore why young learners struggle with causal reasoning even after AR exposure; moreover, limited research has been conducted in disaster-vulnerable regions of the Global South. A systematic review confirms that while AR has positive effects on cognitive outcomes, the specific affordances of mobile AR must be more strongly linked to sound instructional and pedagogical considerations (2025). Second (methodological gap) , prior interventions often treat AR as a standalone visualization tool rather than integrating it into systematically designed, developmentally appropriate instructional materials. Third (conceptual gap) , existing AR applications typically present generic volcano models without contextual anchoring to learners' immediate environment, and the integration of disaster literacy into AR-based science instruction remains underexplored. Recent bibliometric analysis highlights that the systematic integration of AR with scientific literacy aligned with the Sustainable Development Goals remains underexplored, particularly in the Asian context (2026). Fourth (practical gap) , few AR interventions are designed as low-cost, reproducible flipbooks accessible in resource-limited elementary school settings, although AR-based flipbooks have demonstrated feasibility and effectiveness in elementary science contexts (Silmi & Bektiningsih, 2025).

To address these interrelated gaps, this study develops CERIA (Creative Education with Augmented Reality for Science) , an AR-based flipbook designed specifically for fifth-grade elementary students. Unlike previous AR applications that function merely as three-dimensional visualizers, CERIA integrates interactive volcanic process representations with sequenced instructional content, guided inquiry prompts, and formative assessments. This design aligns with previous successful implementations of AR-based flipbooks in elementary science education, which have demonstrated significant improvements in learning outcomes (Silmi & Bektiningsih, 2025). Crucially, CERIA contextualizes abstract volcanic concepts by anchoring them to Mount Ciremai, the active volcano located near the students' school, thereby fostering both conceptual understanding and disaster literacy. Given that Mount Ciremai has been identified as a high-risk volcano requiring targeted mitigation efforts, educational interventions that integrate local volcanic risk into the curriculum are both timely and necessary (Firmansyah et al., 2015). The study is guided by Piaget's cognitive development theory (concrete operational stage), which emphasizes that meaningful learning for elementary students requires observable, tangible experiences—a principle operationalized through CERIA's interactive three-dimensional animations (Piaget, 1972). This theoretical grounding is consistent with constructivist pedagogy, which emphasizes that digital media should align with student learning styles and provide meaningful learning experiences (Rahmadhani et al., 2025). Accordingly, this study addresses the following research question: How does the development and implementation of a locally contextualized AR-based flipbook (CERIA) influence fifth-grade students' conceptual understanding of volcanic eruption processes and disaster literacy? The specific objectives are to: (1) analyze learning needs, (2) design and develop CERIA, (3) assess its viability through expert validation, (4) examine its effectiveness in improving conceptual understanding, and (5) analyze students' responses to its implementation.

This study makes multiple contributions to the field. Theoretically, it provides empirical evidence on how contextualized AR-based instruction can bridge the gap between concrete operational thinking and abstract geoscience concepts, extending Piaget's theory into technology-enhanced, disaster-specific science education (Piaget, 1972). This responds directly to calls in the literature for more sophisticated integration of AR affordances with pedagogical considerations (2025). Empirically, it offers new data from a volcanically active region in Indonesia—a context underrepresented in international AR literature. As noted in recent bibliometric analysis, Asia's contribution to AR and scientific literacy research remains limited, highlighting the need for studies from this region (2026). Practically, it delivers a low-cost, reproducible AR-flipbook that elementary schools in resource-limited settings can adopt to improve both science learning and disaster preparedness. Previous research confirms that AR-based flipbooks are feasible for implementation in elementary schools and can significantly improve learning outcomes (Silmi & Bektiningsih, 2025). The digital flipbook format has also been shown to increase student engagement and strengthen scientific literacy (Rahmadhani et al., 2025). Pedagogically, it demonstrates a replicable student-centered teaching model that integrates local disaster risk into the formal science curriculum, thereby contributing to the global call for disaster-resilient education systems in climate-vulnerable nations. By filling the identified empirical, methodological, conceptual, and practical gaps, this study not only advances theoretical understanding but also provides tangible solutions for improving science education in high-risk volcanic regions.

B. Methods

This study employed a Research and Development (R&D) approach using the ADDIE model (Analysis, Design, Development, Implementation, and Evaluation), which was selected due to its systematic and iterative structure, making it particularly suitable for developing and evaluating instructional media in a structured, replicable manner (Branch, 2009). Given that the primary aim of this study was to produce a locally contextualized Augmented Reality (AR)-based flipbook (CERIA) and to evaluate its effectiveness in improving elementary students' conceptual understanding of volcanic eruption processes, the R&D approach provided a coherent framework that integrated product development with empirical testing. This design aligns with established guidelines for educational technology research, which emphasize the importance of iterative cycles of design, validation, and refinement (Plomp & Nieveen, 2013). Furthermore, to examine the efficacy of the developed product, the study incorporated a one-group pretest–posttest design during the implementation phase, a common approach in preliminary evaluations of instructional interventions (Cohen et al., 2018). This mixed-method design allowed the research team to collect both qualitative data (from classroom observations and teacher interviews) and quantitative data (from pretest–posttest scores and validation questionnaires), thereby providing a comprehensive understanding of the CERIA flipbook's viability and effectiveness.

The participants of this study were 25 fifth-grade students enrolled at SD Negeri Kodasari I, located in Majalengka Regency, West Java, Indonesia, as well as one classroom teacher who participated in semi-structured interviews. The school was selected purposively based on two criteria: (a) its geographical proximity to Mount Ciremai, an active volcano, which made disaster literacy education particularly relevant; and (b) the availability of basic digital infrastructure (shared or personal devices) to support AR-based learning activities. All participating students were aged 10–11 years, in the concrete operational stage of cognitive development (Piaget, 1972), and had access to digital devices during the learning process, ensuring equivalent conditions for engagement with the CERIA flipbook. Data collection was conducted across the five stages of the ADDIE model between August and November 2025. During the analysis stage, the research team conducted classroom observations (two sessions, each 60 minutes) and semi-structured interviews with the classroom teacher (one session, 45 minutes) to identify instructional practices, existing learning resources, and student learning difficulties. In the design and development stages, three-dimensional visualizations of volcanic processes were developed using Assemblr Edu and embedded into a digital flipbook using Heyzine. The implementation stage followed a one-group pretest–posttest design, with students completing a pretest on day one, engaging with the CERIA flipbook in three 70-minute sessions over two weeks, and completing a posttest on the final day. During the evaluation stage, expert validation questionnaires and student response questionnaires were administered to assess the viability and effectiveness of the product.

Four types of instruments were used in this study, each developed specifically for the context of this research. First, expert validation questionnaires (content and media, 15 items each) evaluated the accuracy, depth, appropriateness, visual quality, interactivity, and technical stability of the CERIA flipbook using a 4-point Likert scale (1 = strongly disagree, 4 = strongly agree), adapted from established educational media validation instruments (Akçayır & Akçayır, 2017). Second, a student response questionnaire (11 items, 4-point Likert scale) was administered after the posttest to measure students' perceptions of the CERIA flipbook in terms of effectiveness, usefulness, and motivation. Third, a conceptual understanding test consisting of 20 essay questions was developed based on Bloom's revised taxonomy (Anderson & Krathwohl, 2001), covering cognitive levels C2 (understand), C3 (apply), and C4 (analyze), with sample questions including explanations of magma generation, the effects of a blocked volcanic vent, and comparisons of eruption mechanisms between Mount Ciremai and hypothetical volcanoes. Fourth, semi-structured interview guidelines and observation protocols were used to collect qualitative data during the analysis stage. Prior to the main study, the conceptual understanding test was validated on a separate sample of 25 fifth-grade students from a different school to minimize bias (Cohen et al., 2018). Item validity was assessed using the Pearson correlation coefficient ($\alpha = 0.05$, $df = 23$, r-table = 0.3338), with all 20 items exceeding the critical value, indicating acceptable validity. Reliability was assessed using Cronbach's Alpha, yielding a coefficient of α = 0.873, which exceeds the accepted threshold of 0.70 for educational research (Taber, 2018), indicating high internal consistency.

Table 1. Criteria for Data Interpretation

Percentage Range	Expert Validation Criteria	Student Response Criteria
76% – 100%	Very Valid	Strongly Agree
56% – 75%	Valid	Agree
40% – 55%	Less Valid	Disagree
0% – 39%	Invalid	Strongly Disagree

Data were analyzed using descriptive statistics, inferential statistics, and effect size analysis, with all statistical analyses performed using SPSS version 26.0 (IBM Corp., Armonk, NY, USA). Descriptive analysis was used to interpret expert validation scores and student response questionnaire scores, with percentages calculated using the formula (Obtained Score / Maximum Score) × 100%, then interpreted using criteria adapted from Aiken (1985): 76–100% (very valid/strongly agree), 56–75% (valid/agree), 40–55% (less valid/disagree), and 0–39% (invalid/strongly disagree). Before conducting inferential analysis, the normality of the pretest and posttest data was assessed using the Shapiro–Wilk test, which is appropriate for small sample sizes ($n < 50$) (Razali & Wah, 2011). The results indicated that the pretest data were not normally distributed ($W = 0.891$, $p = 0.022 < 0.05$), while the posttest data were normally distributed ($W = 0.971$, $p = 0.907 > 0.05$). Consequently, the non-parametric Wilcoxon Signed Rank Test was selected to compare pretest and posttest scores, with a significance level of $p \leq 0.05$ considered statistically significant. To measure the magnitude of improvement in students' conceptual understanding following the intervention, Normalized Gain (N-Gain) analysis was employed (Hake, 1998), using the formula (Posttest Score – Pretest Score) / (Maximum Possible Score – Pretest Score), with interpretations of N-Gain ≥ 0.7 (high effectiveness), 0.3 ≤ N-Gain < 0.7 (moderate effectiveness), and N-Gain < 0.3 (low effectiveness). To ensure the trustworthiness of the qualitative data collected during the analysis stage (classroom observations and teacher interviews), several strategies were employed: triangulation by cross-verifying observational field notes with interview transcripts and relevant school documents; member checking by returning the transcribed interview to the participating teacher for verification of accuracy and interpretation; prolonged engagement through two separate observation sessions conducted one week apart; and reflexivity through the use of a researcher journal documenting personal assumptions, biases, and decisions throughout the data collection and process (Lincoln & Guba, 1985; Korstjens & Moser, 2018).

Table 2. Inferential Analysis and N-Gain Criteria

Analysis Technique	Criteria	Interpretation
Wilcoxon Signed Rank Test	$p \leq 0.05$	Notable distinction (effective)
	$p > 0.05$	No discernible change
N-Gain Analysis	N-Gain ≥ 0.7	High progress
	0.3 ≤ N-Gain < 0.7	Moderate progress
	N-Gain < 0.3	Minimal progress

This research was conducted in accordance with the ethical principles outlined in the Declaration of Helsinki. Prior to data collection, the research team obtained written informed consent from the parents or legal guardians of all participating students, as well as from the classroom teacher. The consent form clearly explained the purpose of the study, the procedures involved, the voluntary nature of participation, and the right to withdraw at any time without penalty. To protect participant confidentiality, all names and identifying information were replaced with pseudonyms in transcripts, analyses, and reports. Data files (audio recordings, transcripts, test scores) were stored on a password-protected university server accessible only to the research team. No incentives were provided to participants to avoid undue influence. Additionally, permission to conduct research at SD Negeri Kodasari I was obtained from the school principal and the Majalengka District Education Office. The authors acknowledge several methodological limitations that should be considered when interpreting the findings. First, the one-group pretest–posttest design lacks a control group, which limits the ability to establish causality definitively. Second, the sample size of 25 students, while adequate for preliminary analysis, limits the generalizability of the findings to other populations and contexts. Third, the posttest was administered immediately after the intervention, leaving the durability of learning gains over time unexamined. Future research should address these limitations by employing randomized controlled trials, larger and more diverse samples, and delayed posttest measures to assess long-term retention of conceptual understanding.

C. Results and Discussion

Feasibility of CERIA as an Augmented Reality-Based Learning Media

The feasibility of CERIA was evaluated through expert validation involving media and content specialists. As presented in Table 1, both dimensions achieved very high validity scores, indicating that the developed flipbook met the technical, pedagogical, and curricular requirements for implementation in elementary science learning.

Table 3. Expert Validation Results of CERIA

Validation Aspect	Mean Score (%)	Category
Media Validation	90.83	Very Valid
Content Validation	94.44	Very Valid
Average	92.64	Very Valid

The media validation score of 90.83% indicates that CERIA possesses strong visual quality, navigational clarity, and functional integration of Augmented Reality features. Nevertheless, experts identified minor weaknesses related to layout proportionality and visual composition. Such findings are important because elementary students are particularly vulnerable to extraneous cognitive load generated by poorly organized visual information. According to Cognitive Load Theory, ineffective visual arrangements may interfere with information processing and reduce learning efficiency (Sweller, 1988). Consequently, revisions were undertaken to optimize spacing, object scaling, and contrast ratios, thereby improving visual ergonomics and usability.

Content validation yielded an even higher score (94.44%), confirming that the instructional materials were scientifically accurate, developmentally appropriate, and aligned with the Merdeka Curriculum. However, experts noted that several components related to student engagement and collaborative learning could be further strengthened. To address this issue, stimulus questions and reflective prompts were incorporated to activate prior knowledge and encourage interaction. This refinement is consistent with constructivist learning principles, which emphasize the importance of active knowledge construction through inquiry and discussion (Fosnot & Perry, 2013). Overall, the validation results demonstrate that CERIA fulfills both pedagogical and technological quality standards, supporting its readiness for classroom implementation.

Effects of CERIA on Students' Conceptual Understanding

The effectiveness of CERIA was assessed using pretest-posttest comparisons, Wilcoxon signed-rank analysis, and normalized gain (N-Gain) scores. The descriptive statistics are presented in Table 4.

Table 4. Students' Learning Achievement Before and After Intervention

Test	Mean	SD
Pretest	41.80	16.34
Posttest	82.64	10.21

The findings reveal a substantial increase in students' conceptual understanding following the intervention. The mean score nearly doubled from 41.80 to 82.64, indicating that students acquired considerable knowledge regarding volcanic eruption processes. More importantly, all students achieved the minimum mastery criterion after using CERIA, suggesting that the intervention successfully supported learning across different achievement levels. To determine whether this improvement was statistically significant, a Wilcoxon signed-rank test was conducted. The results are summarized in Table 5.

Table 5. Wilcoxon Signed-Rank Test Results

Z Value	p-value	Interpretation
-4.374	< 0.001	Significant Difference

The significant result confirms that the observed improvement was not attributable to random variation. Beyond statistical significance, practical significance was evaluated using N-Gain analysis (Table 4).

Table 6. N-Gain Analysis Results

Mean N-Gain	Category
0.73	High

The high N-Gain score demonstrates that CERIA generated meaningful conceptual change rather than merely improving test performance. This outcome can be explained by the affordances of Augmented Reality, which enable students to visualize dynamic geological processes that are otherwise difficult to represent through conventional textbooks. Volcanic eruptions involve invisible and complex mechanisms such as magma movement, pressure accumulation, and pyroclastic flows. Through AR visualization, these processes become observable and interactive, allowing students to build richer mental models. This finding supports Mayer's Cognitive Theory of Multimedia Learning (2014), which argues that learning is enhanced when verbal explanations are integrated with coherent visual representations. The results also align with previous AR studies in science education that reported significant gains in conceptual understanding through immersive visualization and interactive exploration.

Students' Perceptions of CERIA

Students' perceptions of CERIA were evaluated across three dimensions: effectiveness, usability, and motivation. The results are presented in Table 5.

Table 7. Student Responses toward CERIA

Dimension	Percentage (%)	Category
Effectiveness	98.00	Very Positive

Dimension	Percentage (%)	Category
Usability	85.00	Very Positive
Motivation	90.75	Very Positive
Overall Response	91.25	Very Positive

The overall response rate of 91.25% indicates a highly positive acceptance of CERIA among elementary students. The effectiveness dimension achieved the highest score (98%), suggesting that students perceived the AR-supported learning experience as highly beneficial for understanding volcanic eruption concepts. This perception corresponds closely with the significant learning gains observed in the posttest results, reinforcing the argument that the instructional design successfully facilitated conceptual comprehension.

Interestingly, usability received the lowest score among the three dimensions, although it remained within the "very positive" category. Informal student feedback indicated occasional difficulties in scanning QR codes under poor lighting conditions and slower loading times on older devices. Similar technical constraints have been widely documented in AR education research, where device compatibility and infrastructure limitations often influence user experience. Nevertheless, the high motivation score (90.75%) demonstrates that the immersive and interactive nature of AR successfully stimulated students' curiosity and engagement. Consistent with Self-Determination Theory (Deci & Ryan, 2000), CERIA appears to support learners' needs for autonomy, competence, and social interaction, thereby promoting intrinsic motivation and sustained engagement.

Educational Implications

The combined evidence from expert validation, learning outcomes, and student perceptions suggests that CERIA represents an effective and scalable approach for teaching abstract scientific concepts in elementary education. The findings highlight three important implications. First, localized AR-based learning media can bridge the gap between abstract scientific phenomena and students' concrete experiences. Second, iterative design refinement based on expert feedback is essential for maximizing pedagogical effectiveness. Third, while AR technology offers substantial educational benefits, successful implementation remains dependent on adequate technological infrastructure and device accessibility. Although the present study provides promising evidence, several limitations should be acknowledged, including the absence of a control group, the relatively small sample size, and the short intervention period. Future studies should employ quasi-experimental or randomized controlled designs, incorporate delayed posttests to examine knowledge retention, and explore broader learning outcomes such as critical thinking, scientific reasoning, and disaster preparedness behaviors. Such investigations would strengthen the evidence base regarding the long-term effectiveness and scalability of AR-based learning interventions in elementary science education.

The very high feasibility scores achieved by CERIA (media validation = 90.83%, content validation = 94.44%) indicate that the AR-based flipbook met rigorous technical, pedagogical, and curricular standards required for implementation in elementary science education. The minor weaknesses identified by experts—particularly regarding layout proportionality and visual composition—reflect the delicate balance between visual richness and cognitive clarity. This finding aligns with Cognitive Load Theory (Sweller, 1988), which posits that poorly organized visual information imposes extraneous cognitive load, especially for concrete operational learners (Piaget, 1972) who are still developing visuospatial processing abilities. The subsequent revisions (optimizing spacing, object scaling, and contrast ratios) were theoretically grounded efforts to reduce extraneous load and free cognitive resources for germane processing—the construction of accurate mental models of volcanic processes. Furthermore, the addition of stimulus questions and reflective prompts in response to expert feedback reflects a constructivist pedagogical orientation (Fosnot & Perry, 2013), where meaningful learning occurs through active inquiry and reflection rather than passive reception. Unlike AR applications that function merely as 3D visualizers, CERIA embeds guided prompts that activate prior knowledge and encourage prediction—design features that distinguish this study from previous AR research (Akçayır & Akçayır, 2017). The implication for instructional design is clear: formative evaluation and iterative refinement based on expert feedback are not optional add-ons but essential processes for maximizing pedagogical effectiveness, particularly when designing for young learners with developing cognitive capacities.

The substantial improvement in students' conceptual understanding—from a pretest mean of 41.80 to a posttest mean of 82.64, with all students achieving mastery—requires explanation beyond mere statistical significance. The high N-Gain score (0.73) indicates that CERIA generated meaningful conceptual change rather than superficial test performance improvement. This outcome can be explained by the unique affordances of AR technology when applied to geoscience education. Volcanic eruption processes (magma generation, subsurface pressure accumulation, pyroclastic flows) are inherently invisible and dynamic—precisely the type of content that concrete operational learners struggle with because they cannot directly observe these phenomena (Piaget, 1972). CERIA transforms these invisible processes into observable, interactive, and manipulable 3D visualizations, thereby operationalizing Piaget's theoretical principle in a technology-enhanced environment. This explanation is strongly supported by Mayer's (2014) Cognitive Theory of Multimedia Learning, which argues that learning is enhanced when verbal explanations are integrated with coherent visual representations and when learners can actively control the pace of presentation. The finding extends previous AR research (Prasetya et al., 2024) in two important ways. First, while prior studies used generic volcano models, CERIA contextualized content to Mount Ciremai—an active volcano in students' immediate environment—thereby enhancing personal relevance and disaster literacy. Second, most previous AR effectiveness studies were conducted in high-income countries with robust infrastructure; this study demonstrates that AR can be effective even in resource-limited rural Indonesian settings when designed as low-cost, web-based applications. The theoretical implication is significant: Piaget's developmental constraints can be mediated through well-designed technological scaffolds, suggesting that abstract content is not inherently inaccessible to concrete operational learners when appropriate cognitive tools are provided.

Students' perceptions of CERIA revealed an interesting pattern: effectiveness was rated exceptionally high (98%), usability was comparatively lower (85%—still very positive), and motivation remained high (90.75%). This pattern warrants careful interpretation. The high effectiveness perception aligns with objective learning gains, indicating that students accurately recognized the cognitive benefits of AR-based instruction—a convergence between subjective and objective measures that strengthens the validity of both. The lower usability score reflects real technical constraints: QR code scanning difficulties under poor lighting and slower loading times on older devices. These constraints are well-documented in AR education research (Akçayır & Akçayır, 2017) and are particularly salient in resource-limited settings. However, the finding that motivation remained high (90.75%) despite these technical frustrations is theoretically significant. According to Self-Determination Theory

(Deci & Ryan, 2000), intrinsic motivation is enhanced when learning environments support autonomy (freedom to explore at one's own pace), competence (successful task completion), and relatedness (social interaction). CERIA appears to support all three needs, and the immersive, novel nature of AR may be sufficiently engaging to overcome moderate technical frustrations—at least in the short term. This finding extends previous motivation research (Syahputra et al., 2024) by demonstrating that high motivation can be achieved even when usability is not perfect, provided that the core learning experience is perceived as effective and personally meaningful. The practical implication for teachers and school administrators is nuanced: while technical infrastructure improvements (adequate lighting, updated devices) would enhance usability, the lack of perfect conditions should not deter AR implementation, as motivational and cognitive benefits may still be realized. Simple, low-cost solutions—such as printing QR codes on high-contrast paper and strategic device charging station placement—can mitigate some identified constraints.

The combined evidence from this study generates three interconnected educational implications. First, localization amplifies effectiveness. By anchoring abstract volcanic concepts to Mount Ciremai—a volcano geographically proximate to students' homes—CERIA transformed generic geoscience into personally relevant, potentially life-saving knowledge. This finding suggests that AR-based science instruction in disaster-prone regions should prioritize local contextualization over generic content, as personal relevance likely enhances both cognitive engagement and disaster literacy outcomes. This implication extends beyond volcanology to earthquake zones, flood-prone areas, and tsunami-risk coastal communities where science education can simultaneously serve academic and disaster preparedness goals. Second, iterative design based on expert feedback is essential. The revisions undertaken in response to validation (layout optimization, reflective prompt integration) were not minor cosmetic changes but theoretically grounded improvements that likely contributed to the high N-Gain score. This finding underscores the value of formative evaluation in educational design research (Plomp & Nieveen, 2013) and suggests that researchers should allocate sufficient time and resources for multiple design-refinement cycles. Third, infrastructure matters, but not as a prerequisite. While technical constraints (lighting, device age) affected usability, they did not prevent significant learning gains or high motivation. This finding carries an important policy implication: rather than waiting for perfect technological infrastructure (which may never arrive in resource-limited settings), schools and policymakers should adopt a "good enough" approach—implementing AR-based interventions with available resources while systematically addressing the most critical usability barriers. However, this does not diminish the need for infrastructure investment; rather, it suggests that implementation and infrastructure improvement should proceed in parallel rather than sequentially.

Despite the promising findings, six methodological limitations must be acknowledged. First, the one-group pretest–posttest design lacks a control group, limiting causal inference. Second, the sample size (n=25) limits generalizability. Third, the immediate posttest leaves knowledge retention unexamined. Fourth, outcome measures focused on conceptual understanding and motivation, excluding critical thinking, scientific reasoning, or disaster preparedness behaviors. Fifth, implementation fidelity may have varied due to unmeasured device and environmental differences. Sixth, potential researcher bias (the lead researcher developed and evaluated CERIA) cannot be entirely eliminated. Addressing these limitations defines the future research agenda: randomized controlled trials with control groups, larger and more diverse samples across multiple volcanic regions, delayed posttests to assess retention, broader outcome measures including disaster preparedness behaviors, systematic investigation of moderating contextual factors, and independent evaluations by researchers not involved in product development. Despite these limitations, this study makes three substantive contributions. Theoretically, it demonstrates that Piaget's concrete operational constraints can be mediated through AR-based scaffolds, extends Mayer's multimedia principles to geoscience education, and provides empirical support for Self-Determination Theory's applicability in AR-enhanced learning environments. Empirically, it provides new data from a previously underrepresented context—rural Indonesia, a volcanically active region of the Global South—responding to calls for more diverse geographical representation in AR research (2026). Practically, it delivers a low-cost, reproducible, web-based AR-flipbook that elementary schools in resource-limited settings can adopt to simultaneously advance science achievement and disaster literacy—a dual goal of particular urgency in an era of increasing climate-related disasters and volcanic activity.

D. Conclusion

This study aimed to develop and evaluate CERIA (Creative Education with Augmented Reality for Science) as an Augmented Reality-based learning medium to facilitate elementary school students' understanding of volcanic eruption concepts. The findings demonstrate that CERIA is highly feasible and effective for science learning, as evidenced by excellent validation results from media experts (90.83%) and content experts (94.44%). Furthermore, students' conceptual understanding improved substantially, reflected in an N-Gain score of 0.73, which falls within the high category. The overwhelmingly positive student responses (91.25%) further indicate that CERIA successfully enhances learner engagement and interest in science learning. These results suggest that the integration of structured instructional content with interactive Augmented Reality technology can effectively transform abstract scientific concepts into more concrete and meaningful learning experiences. From a practical perspective, CERIA can serve as a supplementary instructional medium that supports student-centered learning through guided exploration, collaborative discussions, and formative assessment activities. Moreover, the approach may be adapted to other disaster-related topics to strengthen disaster literacy among elementary school students.

Despite these contributions, several limitations should be acknowledged. The use of a one-group pretest–posttest design without a control group restricts the ability to establish strong causal relationships between the intervention and learning outcomes. In addition, the relatively small sample size and short intervention period may limit the generalizability of the findings. The study also did not investigate long-term knowledge retention or students' behavioral preparedness in disaster situations. Therefore, future research is encouraged to employ quasi-experimental designs involving control groups to enhance the validity and robustness of the findings. Longitudinal studies are also needed to examine the sustainability of learning outcomes through delayed post-tests administered over extended periods. Furthermore, future investigations should broaden the scope of assessment to include higher-order thinking skills and disaster preparedness behaviors, while implementing CERIA across diverse educational settings to provide a more comprehensive understanding of its effectiveness, scalability, and broader educational impact.

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