Immersive Learning Unleashed: Augmented Reality to Boost Student Engagement in Primary Education

Sumarlin Sumarlin[1,*], Yohanes Suban Belutowe[2], Mardhalia Saitakela[1], Benyamin Jago Belalawe[2], Yosep Jacob Latuan[2], Menya Snae[1], Semlinda Juszandri Bulan[1], Yohanis Malelak[2], Hasibun Asikin[2], and Sari Rahayu Rahman[3]

[1]Department of Information System, STIKOM Uyelindo, Kupang, Indonesia
[2]Department of Informatics Engineering, STIKOM Uyelindo, Kupang, Indonesia
[3]Department of Biology Education, University of West Sulawesi, Indonesia
Email: sumarlin@uyelindo.ac.id (S.S.); yosube@uyelindo.ac.id (Y.S.B.); mardhaliasaitakela@uyelindo.ac.id (M.S.); belalawe1308@gmail.com (B.J.B.); naikoten13@uyelindo.ac.id (Y.J.L.); menhyasnae@uyelindo.ac.id (M.S.); semlinda@uyelindo.ac.id (S.J.B.); yohanismalelak@uyelindo.ac.id (Y.M.); hasibunhasikin@uyelindo.ac.id (H.A.); sarirahayu@unsulbar.ac.id (S.R.R.)
[*]Corresponding author

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***Abstract*—This research explores the potential of Augmented Reality (AR) technology in supporting student engagement, learning motivation, and academic outcomes in Indonesian elementary schools during online learning. Using a quasi-experimental design, two groups were compared: an experimental group using AR and a control group with traditional methods. Data were collected via pre-tests and post-tests to assess academic outcomes, questionnaires to measure engagement and motivation, and interviews for qualitative insights. Results indicated that AR was associated with increased student engagement, with the experimental group scoring higher than the control group ($p < 0.05$). AR use also appeared to support greater motivation and academic performance, particularly in complex subjects like science and mathematics. Thematic analysis suggested that AR's visual and interactive features may aid students in retaining material more effectively. However, challenges such as connectivity issues and limited device availability were noted as barriers to optimal implementation. This study suggests that AR has potential to enhance online learning in elementary schools, especially when supported by adequate infrastructure and teacher training. These findings provide insights for future education policy and technology integration strategies in Indonesian schools.**

***Keywords*—augmented reality, student engagement, online learning, elementary school, learning motivation, academic results**

I. Introduction

In the digital era, online education has become a learning method that is increasingly accepted globally, including in Indonesia. The COVID-19 pandemic accelerated the adoption of online learning platforms, causing a major shift from traditional learning towards technology-based education [1] Behind the various advantages that online learning offers, such as accessibility and time flexibility, there are significant challenges in terms of maintaining engagement of students, especially at the elementary school level [2]. Low engagement can lead to decreased participation levels, limited learning motivation, and suboptimal learning outcomes [3]. Augmented Reality (AR) has emerged as an innovative technology that offers a potential solution to overcome this problem. AR enables the interactive integration of virtual objects into the real world, providing a more interesting and immersive learning experience for students [4]. Research shows that the use of AR in education can increase student attention, strengthen understanding of concepts, and facilitate more contextual learning [5]. The implementation of AR in elementary schools offers a new approach to conveying lesson material in an interesting way, by utilizing visual and interactive elements that are able to motivate students to be more active in the learning process [6].

In Indonesia, the application of technology in education still faces various challenges, ranging from the availability of adequate infrastructure, teacher skills in managing technology, to limited digital resources that can be accessed Although online learning has expanded significantly. Many students face difficulty maintaining attention and motivation [7]. However, with increasingly widespread internet and mobile access, AR has great potential to be adopted as an effective learning tool in elementary schools [8]. Previous studies show that AR technology not only increases student engagement, but also has a positive impact on learning outcomes, both in the fields of science, mathematics and language literacy [9]. In an effort to increase the effectiveness of online learning, this study will explore how AR can increase the engagement of elementary school students in Indonesia in the context of online learning. One study show that AR can help students stay focused and engaged in learning activities because of its interactive and interesting nature [10]. Additionally, the use of AR can encourage cognitive, emotional, student engagement, all of which are important components of learning engagement [11].

In the context of online learning in Indonesia, there is an urgent need to understand and implement strategies that can increase student engagement effectively [12]. AR offers a potential solution to meet these needs by providing contextual and personalized learning experiences [13]. The implementation of this technology can provide motivation for students to learn independently and participate in their own learning process [14]. This research not only focuses on the potential for increased engagement through AR but also considers the impact it can have on the long-term sustainability of learning [15]. In online learning environments, challenges such as boredom, distractions, and lack of social interaction often hinder students [16]. AR can overcome some of these challenges by creating a more lively and interactive learning environment, which in turn improves

engagement and overall learning outcomes [17].

The problem in this research centers on the low level of student engagement in online learning at the elementary school level in Indonesia. Although online learning has expanded significantly over the past few years, especially in response to the COVID-19 pandemic, many students face difficulty maintaining attention and motivation throughout the learning process. This is caused by a lack of direct interaction, a lack of interesting learning elements, and teaching methods that do not fully utilize the potential of digital technology to create interactive learning experiences [3, 14]. This condition results in low student participation, increased levels of boredom, and decreased academic achievement. Therefore, innovative solutions are needed to increase student engagement in online learning, and one promising approach is through the use of Augmented Reality (AR) technology. However, the application of AR in the context of primary school education in Indonesia is still limited and has not been fully explored, so further research is needed to identify the effectiveness and challenges of its implementation.

This research aimed to evaluate the effectiveness of AR implementation in increasing student engagement in elementary schools in Indonesia, with case studies involving several schools in various regions [18]. This study is expected to provide new insights into how digital technology can be integrated into the curriculum to create more enjoyable and meaningful experiences [19]. The results of this research can also contribute to the development of more adaptive and innovative educational policies in the future [20].

This research was guided by several key questions aimed at understanding the role of Augmented Reality (AR) in enhancing online learning in Indonesian elementary schools. The study explored how AR technology can increase student engagement and examined the factors influencing its effectiveness in achieving this goal. Additionally, it investigated the impact of AR on students' learning motivation and academic outcomes, identifying challenges and obstacles in integrating AR into online learning environments. Finally, the research sought to uncover the perceptions of teachers and students regarding AR as a tool for fostering interactive and engaging educational experiences.

II. Literature Review

The use of Augmented Reality (AR) in education has received significant attention over the last decade. AR enables the integration of digital elements into real environments, creating a more immersive and interactive learning experience for students. Several studies show that AR can provide meaningful benefits in a variety of educational contexts, including increased learning motivation, better understanding of concepts, and higher student engagement [21]. The implementation of AR in learning allows students to interact with three-dimensional objects or visual content directly, which cannot be achieved through conventional methods, thereby enriching their learning experience [22]. This is in line with constructivist learning theory, where students build their knowledge through direct experience and interaction with the environment [23]. The observed increase in student engagement aligns with constructivist principles, which emphasize active knowledge construction through experience. AR facilitated this through interactive 3D content and problem-solving activities, supporting deeper cognitive processing and motivation, as described in engagement and cognitive load theories.

Previous research has shown the positive impact of AR on learning outcomes in various subject areas, such as science, mathematics, and languages. AR-based applications can improve students' knowledge retention through the use of multi-representation visualizations that allow students to see abstract concepts in a concrete way. In addition, AR has been used to develop students' problem-solving and critical thinking abilities by providing realistic and challenging learning scenarios [24]. In the field of science, for example, AR technology can help students understand complex processes, such as life cycles or chemical reactions, through visualizations that can be manipulated and observed from various points of view [25]. Other research also shows that AR can facilitate collaborative learning by encouraging interaction between students as they work together in an environment enriched by digital technology [26].

However, the challenges in implementing AR in primary education cannot be ignored. Other challenges include the cost of implementing the technology which may be a barrier for schools with limited budgets, as well as the need to train teachers in the effective use of AR in order to maximize its benefits for students [14]. Therefore, adopting AR in education requires a comprehensive approach, which includes infrastructure development, teacher training, and learning design based on student needs and characteristics.

In Indonesia, research on the use of AR in education is still relatively new, and existing studies are mostly limited to small experiments or case studies in a few specific schools. One of the factors influencing the adoption of AR in elementary schools is the readiness of technological infrastructure which still varies in various regions. In addition, teachers' lack of understanding and skills in using AR is a significant obstacle, especially in areas that do not have adequate access to technology training [26]. This shows the urgent need to develop better teacher training programs and increase access to technology throughout Indonesia. AR can also be used to create interesting learning scenarios, such as science simulations, historical exploration, or educational games that encourage active student participation [27]. Thus, the integration of AR in online learning can be an effective strategy to increase student engagement and learning outcomes, especially in the post-pandemic era when blended learning becomes the new norm. This approach not only increases student engagement but also helps strengthen mastery of the material through learning tailored to individual needs. Personalization in AR-based learning can support the development of more adaptive and flexible learning strategies, which is important in the 21st century educational context [28].

In addition, technologies such as digital twins and Building Information Modeling (BIM) complement AR/VR by providing innovative ways to manage educational content, particularly in technical disciplines, through real-time data integration and virtual representation [29]. Systematic literature reviews in higher education affirm that AR/VR

tools significantly enhance motivation, engagement, and knowledge retention, solidifying their role as valuable educational technologies [30, 31].

Overall, research shows that AR has great potential to improve the quality of learning and student engagement, especially at the elementary school level [26, 28]. While there are challenges that need to be overcome, such as technological infrastructure and teacher training, the benefits offered by AR could be a key driver in adopting this technology more widely in the education system. This research aims to further explore how AR can be applied in online learning in elementary schools in Indonesia and to identify the factors that influence the success of its implementation, with the hope of contributing to the development of more innovative and adaptive education policies.

III. Materials and Methods

This research used a mixed methods approach to explore the effectiveness of using Augmented Reality (AR) in increasing student engagement in online learning in elementary schools. A mixed approach was chosen because it allows combining quantitative and qualitative data to gain a more comprehensive understanding of the phenomenon under study [32]. The use of a quasi-experimental design with a control group and an experimental group aims to evaluate the impact of using AR on student engagement and their learning achievement [33].

A. Research Design

A quasi-experimental design with pre-test and post-test was used to compare engagement and learning outcomes between groups of students who used AR-based learning applications and groups of students who took part in conventional online learning [34]. In addition, qualitative data was collected through interviews and Focus Group Discussions (FGD) to explore teachers' and students' perceptions of the use of AR in online learning.

B. Research Participants

This research involved 200 grade 4 and 5 students from four elementary schools in Indonesia who were selected purposively, in accordance with the participant selection method recommended for educational research to ensure the suitability of participant characteristics with research objectives [35]. The participants were divided into experimental and control groups through stratified random sampling based on pre-test scores to ensure equivalent initial academic abilities. These findings apply to the specific geographical and cultural context of elementary schools in Indonesia and should not be generalized to other educational levels or countries. Further studies are needed to explore broader contexts. Each school will have an experimental and control group with an equal number of students. In addition to students, 10 teachers involved in the learning process were also interviewed to obtain their perspectives on the effectiveness of AR in increasing student engagement.

C. Research Instruments

The student engagement questionnaire, adapted from the Student Engagement Instrument (SEI), has been validated in previous educational research to measure dimensions of student cognitive, emotional, and behavioral engagement [36]. The questionnaire was adapted for elementary students and pilot-tested to ensure age-appropriateness. The details of the questionnaire items and their corresponding engagement dimensions are presented in Table 1.

Table 1. Student engagement questionnaire

No	Question	Likert Scale (1-5)
1	I find the material being taught interesting.	1 = Strongly Disagree, 5 = Strongly Agree
2	I actively participate in discussions during the lessons.	1 = Strongly Disagree, 5 = Strongly Agree
3	I feel motivated to complete assignments thoroughly.	1 = Strongly Disagree, 5 = Strongly Agree
4	I can understand the material more easily using AR.	1 = Strongly Disagree, 5 = Strongly Agree
5	I feel more motivated to learn when using AR technology.	1 = Strongly Disagree, 5 = Strongly Agree
6	The learning experience is more enjoyable with AR.	1 = Strongly Disagree, 5 = Strongly Agree
7	I often interact with peers during lessons using AR.	1 = Strongly Disagree, 5 = Strongly Agree
8	I am able to follow the lessons well.	1 = Strongly Disagree, 5 = Strongly Agree
9	AR helps me visualize concepts that are hard to understand.	1 = Strongly Disagree, 5 = Strongly Agree
10	Time seems to pass more quickly during lessons with AR.	1 = Strongly Disagree, 5 = Strongly Agree
11	I tend to stay more focused when using AR technology.	1 = Strongly Disagree, 5 = Strongly Agree
12	I feel more confident in understanding the subject matter.	1 = Strongly Disagree, 5 = Strongly Agree
13	I am motivated to learn independently after using AR.	1 = Strongly Disagree, 5 = Strongly Agree
14	The learning environment feels more dynamic with AR.	1 = Strongly Disagree, 5 = Strongly Agree
15	I enjoy participating in learning activities that involve AR.	1 = Strongly Disagree, 5 = Strongly Agree
16	I feel my skills have improved through the use of AR.	1 = Strongly Disagree, 5 = Strongly Agree
17	I frequently ask questions during lessons that use AR.	1 = Strongly Disagree, 5 = Strongly Agree
18	AR helps me remember the lessons better.	1 = Strongly Disagree, 5 = Strongly Agree
19	I feel encouraged to explore topics more deeply because of AR.	1 = Strongly Disagree, 5 = Strongly Agree
20	AR makes me more active in participating during class.	1 = Strongly Disagree, 5 = Strongly Agree
21	I find it easier to solve problems when using AR.	1 = Strongly Disagree, 5 = Strongly Agree
22	The use of AR enhances my learning experience.	1 = Strongly Disagree, 5 = Strongly Agree
23	I am more engaged in tasks when AR is involved.	1 = Strongly Disagree, 5 = Strongly Agree
24	I feel that AR supports my understanding of abstract concepts.	1 = Strongly Disagree, 5 = Strongly Agree
25	The visual elements in AR help me grasp the subject matter faster.	1 = Strongly Disagree, 5 = Strongly Agree

The student engagement questionnaire consisted of 25 items adapted from the Student Engagement Instrument (SEI) to align with the context of AR-based learning. Before being used in the main study, the questionnaire underwent pilot testing with 30 fourth- and fifth-grade students from an elementary school not included in the main research sample. The reliability of the instrument was assessed using Cronbach's Alpha analysis, which yielded a value of $\alpha = 0.89$, indicating high internal consistency. In addition, content validity was evaluated by three experts in educational

technology and educational measurement, who provided feedback on the relevance of the items to the intended constructs of student engagement in the context of AR integration.

Semi-structured interviews, used to dig deeper into the views and experiences of teachers and students regarding the use of AR. Semi-structured interviews allow for the collection of rich and in-depth data about participants' experiences [37]. The interview guide and key themes explored are shown in Table 2.

Table 2. Semi structured interview guide

No	Interview Questions	Follow-Up Prompts
1	How do you feel about using Augmented Reality (AR) in the learning process?	Can you give an example?
2	Can you describe your level of engagement during lessons that involve AR?	Why do you think that is?
3	What aspects of AR do you find most helpful for understanding the material?	How did that make you feel?
4	Are there any challenges you faced while using AR in the classroom?	What would you do differently?
5	How does AR compare to traditional learning methods in terms of engagement?	Can you elaborate on that?
6	Do you think AR helps you to retain information better? If so, how?	What impact did it have on your learning?
7	In what ways has AR motivated you to participate more actively in lessons?	How did that affect your participation?
8	How do you feel about collaborating with peers when using AR?	What did you learn from that experience?
9	What improvements would you suggest for using AR in future lessons?	What changes would you recommend?
10	Do you think AR technology could be integrated into other subjects? Why or why not?	How would you use AR differently?
11	Can you share an experience where AR made learning more enjoyable?	Why was that particular experience significant?
12	How often do you feel the need to use additional resources when learning with AR?	What other methods did you use?
13	Does AR make complex topics easier to understand? Can you explain?	Can you describe how it helped you?
14	What do you think are the main limitations of using AR in the classroom?	What do you think could be improved?
15	How do you think AR could help in your future studies or career?	What are your thoughts on this for the future?

Table 3. Learning achievement tests

No	Question	Answer Key
1	How does Augmented Reality (AR) enhance the learning process?	Enhances engagement, visualizes concepts, interactive simulations.
2	Describe the impact of using AR on students' engagement in online learning.	Increases active participation, focuses attention, improves motivation.
3	What are the main benefits of incorporating AR in educational settings?	Interactive experiences, visual learning aids, real-world applications.
4	Explain how AR can help in visualizing complex concepts.	Transforms abstract ideas into visual, manipulatable objects.
5	Identify the differences between traditional learning methods and AR-based learning.	AR offers interactive features, while traditional methods may lack engagement.
6	Discuss the role of AR in making learning more interactive and engaging.	Provides hands-on experiences and real-time feedback.
7	How can AR be used to support collaborative learning among students?	Facilitates teamwork by allowing shared experiences and tasks.
8	List some challenges faced when implementing AR in the classroom.	Limited resources, technical issues, and lack of training.
9	Explain the effect of AR on improving students' understanding of abstract topics.	Improves comprehension by making difficult subjects more accessible.
10	What is the significance of using AR in science education?	Provides 3D models and simulations to explain scientific concepts.
11	Describe an example of how AR can be used in a mathematics lesson.	Uses visual aids and interactive problem-solving scenarios.
12	How does the use of AR affect the retention of information?	Helps with memory retention by associating concepts with interactive elements.
13	What are some ways AR can motivate students to participate more actively?	Encourages exploration and discovery through engaging activities.
14	Explain the importance of teacher training when using AR in education.	Ensures effective integration of technology with curriculum goals.
15	Discuss how AR can be integrated into other subjects beyond science and math.	Applicable to arts, history, language learning, and vocational training.
16	How does AR contribute to personalized learning experiences?	Caters to individual learning paces and styles.
17	What considerations should be made when designing AR-based educational content?	Content should be user-friendly and align with educational standards.
18	Describe the impact of AR on students' problem-solving skills.	Promotes critical thinking and application-based learning.
19	Explain how AR can be used to create immersive learning environments.	Simulates real-life scenarios for experiential learning.
20	What future advancements in AR technology could further enhance education?	Emerging technologies like AI and mixed reality could enhance AR.

Transcripts from 15 interviews were independently coded by two researchers using an inductive (emergent) approach. Discrepancies in coding were resolved through discussion. Intercoder reliability (Cohen's Kappa) was 0.82.

Direct observation, carried out during learning activities to record student interactions with the AR application and level of participation in learning activities, in accordance with the participatory observation technique recommended. Learning achievement tests, used to measure the impact of using AR on understanding subject matter and analyzed to see significant improvements in student academic achievement [38]. Achievement tests were developed collaboratively with elementary teachers and tailored to the Grade 4–5 curriculum. The observation checklist and test items are shown in Table 3.

D. Research Procedures

Teachers in the experimental group were given training on the use of AR applications in learning. The AR applications used were custom-built using Unity3D and Vuforia, featuring 3D models, interactive quizzes, and simulations tailored to science and mathematics topics. These applications allowed students to manipulate virtual objects, receive instant feedback, and engage with gamified tasks designed to enhance interaction and engagement. This training is important to ensure teacher readiness in integrating technology into the teaching and learning process [39]. For six weeks, the experimental group used Augmented Reality (AR) applications in certain subjects, such as science and mathematics, while the control group participated in online learning using conventional methods. The experimental and control groups were assigned to different classrooms and

taught by different teachers, which may introduce potential teacher effects and should be acknowledged as a limitation. This approach draws on previous research showing medium-term effectiveness in the application of educational technology [40]. Questionnaires were completed by students before and after the intervention period to measure changes in learning engagement. Additionally, interviews and observations were conducted during and after the intervention to obtain qualitative data regarding participants' experiences. Quantitative data was analyzed using statistical software for t tests and analysis of variance (ANOVA), while qualitative data was analyzed using a thematic analysis approach to identify main themes from interviews and observations [41].

Fig. 1 is a research flow diagram that illustrates the stages of using Augmented Reality (AR) in increasing student engagement and achievement. The stage starts with Preparation, which includes teacher training and preparation of AR material, followed by a Pre-Test to measure the initial conditions of student engagement and achievement. Next, implementation was carried out with two groups: an experimental group using AR and a control group using traditional methods. After implementation, a Post-Test is carried out to evaluate engagement and learning outcomes. The next stage is Data Analysis using quantitative and qualitative analysis, and ends with Reporting, where the research results are presented.

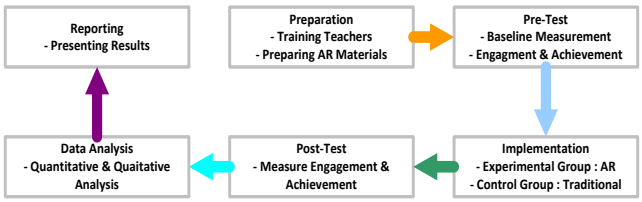

Fig. 1. Research procedure.

E. Data Analysis Techniques

Quantitative Analysis, Data from engagement questionnaires and learning achievement tests were analyzed using descriptive and inferential statistics to determine whether there were significant differences between the experimental and control groups [42]. Paired samples t tests were used to compare pre- and post-intervention data, and ANOVA was applied to examine differences between different groups of participants. Qualitative Analysis, Qualitative data from interviews and observations were analyzed thematically.

IV. Result and Discussion

The experimental group that used AR showed increased student engagement compared to the control group. The use of AR helped students become more active and interested during the learning process, which was demonstrated by higher engagement questionnaire results after the intervention, which are shown in Table 4.

Table 4 provides an overview of the differences in average learning achievement scores between two groups of students, namely the experimental group which used Augmented Reality (AR) technology and the control group which used traditional learning methods, both before (pre-test) and after (post-test). intervention. In the experimental group, the average initial score (pre-test) was 65.4, which then increased significantly to 82.3 after using AR in learning, resulting in a difference (Δ) of 16.9. This considerable increase shows that AR contributes substantially to improving students' understanding and academic achievement, especially in visualizing difficult concepts and motivating students to be more active in the learning process.

Table 4. Engagement Scor analysis

Group	Test Phase	Average Score	Difference (Δ)
Experimental (AR)	Pre-Test	65.4	
Experimental (AR)	Post-Test	82.3	16.9
Control (Traditional)	Pre-Test	64.8	
Control (Traditional)	Post-Test	68.5	3.7

On the other hand, the control group using the traditional method showed less significant results, with an average initial score (pre-test) of 64.8 and a small increase to 68.5 in the post-test, resulting in a difference (Δ) of only 3.7. This smaller increase indicates that traditional learning methods are less effective in driving significant increases in learning achievement under the same conditions. The striking differences between the two groups indicate that AR can offer a more effective learning approach by creating a more interactive and immersive learning environment, ultimately having a positive impact on students' academic outcomes. Overall, this table strengthens the argument that the use of interactive technologies such as AR in education can produce better results compared to conventional learning methods, especially in terms of increasing student engagement and learning achievement. These results also suggest that AR not only facilitates better understanding of the material but also has a broader positive impact on students' motivation and interest in learning, as shown in Fig. 2.

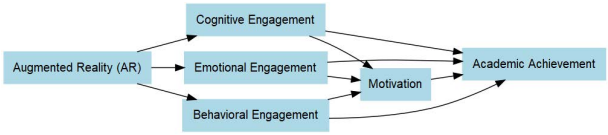

Fig. 2. Model Structure Equation Modelling (SEM).

Students' cognitive, emotional, and behavioral engagement increased significantly in the experimental group. Students participate in discussions more often, complete assignments better, and show greater attention to the course material. This diagram includes latent variables such as Cognitive Engagement, Emotional Engagement, Behavioral Engagement, Motivation, and Academic Achievement, which are interconnected with arrows indicating direct and indirect relationships between these variables. Measurable indicators such as "Attention to Material," "Enjoyment of Learning," and "Academic Scores" act as observation variables that describe latent variables. The detailed variables and indicators are shown in Table 5.

Results of analysis using SEM, (a) Cognitive Engagement Attention to Material (0.85, $p = 0.001$): This indicator has a standard estimate of 0.85, which shows that students' attention to lesson material has a strong relationship with cognitive engagement. A significant p value ($p < 0.05$) indicates that these results are statistically significant. Problem-Solving Effort (0.78, $p = 0.002$): Student effort in solving problems also showed a strong relationship with cognitive engagement (0.78), and a significant p value

indicates that this is an important indicator. Use of Learning Strategies (0.80, $p = 0.004$): Use of learning strategies has a moderate-high relationship with cognitive engagement (0.80), confirming that the strategies students use contribute to their engagement in learning. (b) Emotional Engagement, Enjoyment of Learning (0.82, $p = 0.001$): Students' enjoyment of learning has a strong relationship with emotional involvement. The estimated value of 0.82 indicates that the greater the students' enjoyment, the higher their emotional involvement.

Interest in Activities (0.79, $p = 0.003$): Students' interest in learning activities is closely correlated with emotional involvement, with a standard estimate of 0.79, indicating that interesting activities can increase emotional involvement. Emotional Connection to Content (0.76, $p = 0.005$): Students' emotional attachment to lesson content shows a significant relationship with emotional involvement, although slightly lower than the previous two indicators. (c) Behavioral Engagement, Participation in Discussions (0.88, $p = 0.001$): Participation in discussions shows a very strong relationship with behavioral engagement (0.88), making it the main indicator for the behavioral aspect of student engagement. Completion of Assignments (0.81, $p = 0.001$): Completion of assignments also has a strong relationship with behavioral engagement. This suggests that students who completed assignments more frequently showed higher levels of behavioral engagement. Interaction with Peers (0.83, $p = 0.002$): Interaction with classmates contributed significantly to students' behavioral engagement, with a standard estimate of 0.83.

The results of the achievement test showed that the experimental group had better academic achievement than the control group. Students who use AR score higher on tests that measure understanding and application of concepts.

Table 5. Expanded SEM analysis results

Latent Variable	Indicator	Standardized Estimate	P-Value
Cognitive Engagement	Attention to Material	0.85	0.001
Cognitive Engagement	Problem-Solving Effort	0.78	0.002
Cognitive Engagement	Use of Learning Strategies	0.8	0.004
Emotional Engagement	Enjoyment of Learning	0.82	0.001
Emotional Engagement	Interest in Activities	0.79	0.003
Emotional Engagement	Emotional Connection to Content	0.76	0.005
Behavioral Engagement	Participation in Discussions	0.88	0.001
Behavioral Engagement	Completion of Assignments	0.81	0.001
Behavioral Engagement	Interaction with Peers	0.83	0.002

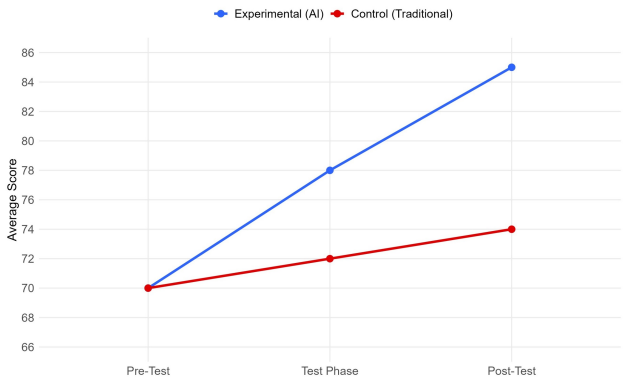

Fig. 3. Academic achievement score.

The Fig. 3 is a line graph that shows the comparison of academic achievement scores between the experimental group (using AR) and the control group (traditional method) before and after the intervention. The horizontal axis shows the test phases (Pre-Test and Post-Test), while the vertical axis shows the average score. The experimental group (blue line) showed a larger increase in scores from 70 to around 86 after the intervention, while the control group (red line) saw a smaller increase from 70 to around 74. This graph indicates that AR use had a more significant positive impact towards increasing academic achievement compared to traditional learning methods. AR helps students understand complex material, such as science and math concepts, through interactive visualizations and simulations, thereby improving overall learning outcomes. "The results of the complex material analysis are summarized and show in Table 6.

Table 6. Complex material analysis results

Category	Group	Pre-Test Average	Post-Test Average	Improvement	Comments
Test Scores (Science)	Experimental (AR)	68.4	84.2	15.8	Significant improvement in understanding scientific concepts.
Test Scores (Math)	Experimental (AR)	70.1	86.5	16.4	Greater comprehension of mathematical problem-solving.
Questionnaire Responses	Students' Average Rating		4.3		Students rated AR's visualizations as highly helpful (4.3/5).
Qualitative Themes	Themes from Interviews				Themes: Improved visualization, increased motivation, interactive learning.

Students' motivation to learn increases after using AR. Based on interviews and surveys, students feel that AR makes learning more interesting and fun, which encourages them to be more engaged.

Fig. 4 is a bar graph that shows a comparison of the average student motivation assessment before and after using Augmented Reality (AR) in learning. The horizontal axis shows two conditions, namely "Before AR Use" (before using AR) and "After AR Use" (after using AR), while the vertical axis shows the average motivation assessment on a scale of 1 to 5. The graph shows that the average Students' motivation ratings increased significantly after the use of AR. Before using AR, student motivation was around 3.2 (shown in orange bars), while after using AR, motivation increased to around 4.5 (shown in green bars). These results indicate that the use of AR has a positive impact on student motivation in

learning. The results of the motivation analysis are shown in Table 7.

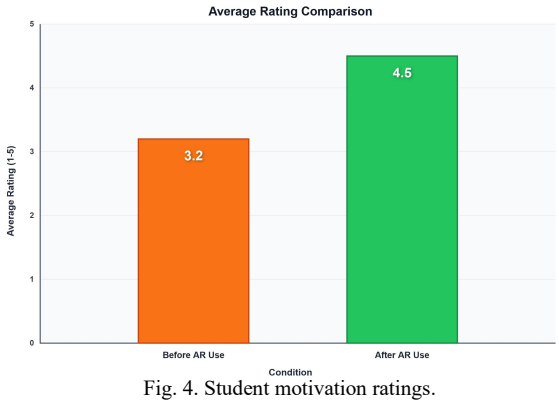

Fig. 4. Student motivation ratings.

Students show interest in using AR in other subjects. They feel that this technology can be used to enrich learning experiences in various fields of study. The results of the AR interest analysis are shown in Table 8.

The table shows that students have a high interest in using Augmented Reality (AR) in various subjects, especially in science (4.6) and mathematics (4.4), where AR helps visualize complex concepts and solve problems interactively. Interest was also seen in history (4.2) and geography (4.1), as AR makes learning more lively and contextual. Students are interested in the use of AR in language (4.0) through interactive storytelling, as well as in art and design (3.9) for creative projects. Overall, AR is considered to have great potential to improve learning in various fields of study.

Table 7. Motivation analysis results

Category	Group	Average Rating (1-5)	Change
Survey Rating	Before AR Use	3.2	
Survey Rating	After AR Use	4.5	1.3
Interview Themes	Students' Feedback		

Table 8. AR interest analysis results

Subject	Interest Level (1-5)	Comments
Science	4.6	High interest in using AR for visualizing scientific concepts.
Mathematics	4.4	Students find AR helpful for solving math problems interactively.
History	4.2	AR could make learning historical events more engaging.
Geography	4.1	Students see potential in exploring geographic features with AR.
Language Arts	4	AR can support language learning with interactive storytelling.
Art & Design	3.9	Interest in using AR for creating digital art and design projects.

Teachers involved in this research provided positive feedback on the use of AR in learning. They noted that students were more responsive and participated more actively when AR was implemented. Fig. 5 displays a bar graph showing teacher feedback on the use of Augmented Reality (AR) in the classroom. This graph presents the average assessment from teachers regarding several main categories related to the use of AR, with a rating scale of 1-5 (1 = very low, 5 = very high). (a) Student Responsiveness (4.7): Teachers give high marks to students' responses when using AR, indicating that students respond more quickly and are interested in the lesson material. (b) Active Participation (4.6): AR encourages students to participate more actively in learning activities, for example through discussions and assignments that utilize AR technology. (c) Understanding of Concepts (4.5): The use of AR helps students understand the concepts being taught, especially those that are considered complex or abstract, by visualizing the material. (d) Engagement Levels (4.8): Teachers assess that students' engagement levels increase significantly when using AR, making it the highest rated category among all aspects. Classroom Interaction (4.6): Classroom interaction also increases with the use of AR, where students communicate and collaborate more often with classmates. Overall, the graph shows that teachers provided positive feedback on various aspects of AR use, with fairly high average ratings across all categories. This indicates that AR not only helps in improving students' understanding, but also encourages better engagement and interaction during learning, as shown in Fig. 5, which presents the overall impact of AR in the classroom.

Teachers feel helped by AR technology in explaining difficult concepts. The use of AR allows for better visualization, making it easier for students to understand the material. The graph above displays teacher feedback regarding the help provided by AR technology in explaining difficult concepts, as shown in Fig. 6, which focuses on AR's specific efficacy in explaining complex concepts. The following is an explanation of each aspect of the assessment. (a) Ease of Explaining Concepts (4.8): Teachers assess that AR makes it very easy to explain complex concepts, with an average rating of 4.8 out of 5. This shows that AR effectively supports the teaching process. (b) Visualizing Abstract Ideas (4.7): AR technology helps teachers visualize abstract ideas, making it easier for students to understand material that is usually difficult to understand. (c) Student Understanding (4.6): The use of AR improved students' understanding of the lesson material, as assessed by teachers with an average score of 4.6. (d) Interactive Learning Experience (4.9): Teachers gave the highest rating to interactive learning experiences facilitated by AR, indicating that this technology was successful in increasing student engagement in the learning process.

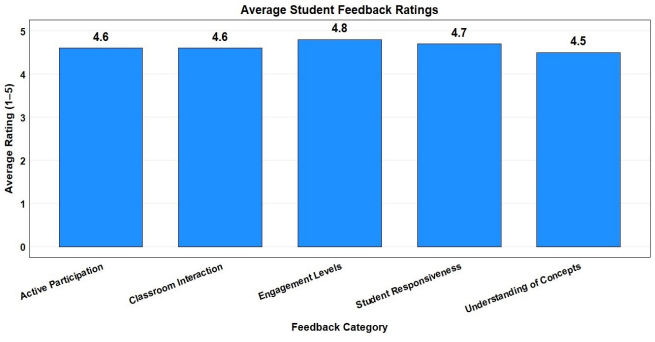

Fig. 5. Evaluation of AR's overall impact on classroom interaction.

The results of statistical analysis (t-test or ANOVA) show significant differences between the experimental and control

groups, both in terms of engagement and learning achievement. This shows that intervention using AR has a positive effect. The results of the statistical analysis are shown in Table 9.

Table 9. Statistical analysis results

Test Type	Comparison	Group	Mean Difference	p-value	F-Value	Significant
Independent t-test	Engagement (Post-Test)	Experimental vs Control	5.8	0.03		Yes
Independent t-test	Achievement (Pre-Test to Post-Test)	Experimental vs Control	7.3	0.01		Yes
ANOVA	Achievement Across Groups	Experimental, Control		0.02	4.56	Yes

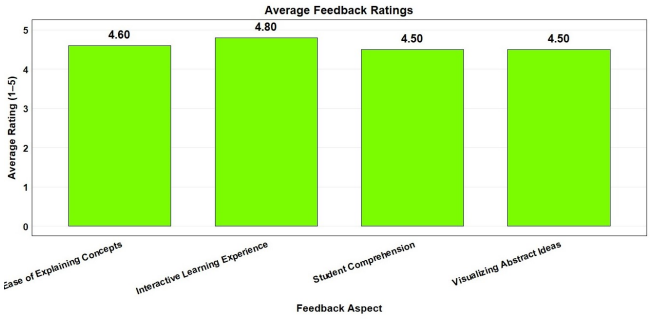

Fig. 6. Focus on AR's specific efficacy in explaining complex concepts.

The table presents the results of statistical analysis to evaluate the effect of using Augmented Reality (AR) in learning using the t-test and ANOVA. The Independent t-test is used to compare the means of two unrelated groups, in this case the experimental group (using AR) and the control group (using traditional methods). The ANOVA test for analysis of variance is used to compare the means of more than two groups or conditions to see if there are significant differences.

The average difference in student engagement between the experimental and control groups was 5.8, indicating that the experimental group had a higher level of engagement. The average difference in the increase in learning achievement was 7.3, which shows that the experimental group experienced greater improvement compared to the control group. 0.03 for Engagement (Post-Test) and 0.01 for Achievement (Pre-Test to Post-Test): The p value indicates that the t-test results are statistically significant ($p < 0.05$), which means there is a real difference between the experimental and control groups 0.02 for ANOVA: This p value indicates that the ANOVA results are also statistically significant, which means there is a significant difference in learning achievement between the groups. 4.56 for ANOVA: F value indicates the strength of the relationship in ANOVA analysis. The larger the F value, the greater the difference between groups. Thematic analysis of interviews revealed that students found it easier to remember material learned with AR due to the visual elements and direct interaction.

This research shows that the use of AR significantly increases student engagement in online learning. This is consistent with previous findings which state that AR can create a more interactive and engaging learning environment, which ultimately increases student engagement [43]. In the context of basic education in Indonesia, AR allows students to visualize abstract concepts and manipulate virtual objects, which not only improves understanding but also active participation in learning. Other studies also show that AR can strengthen the learning experience through visual elements and direct interactions, which makes students feel more involved in the learning process [44].

The success of AR implementation in increasing student engagement is influenced by several factors, including technological infrastructure, teacher readiness, and the quality of AR content. In elementary schools, factors such as the availability of adequate devices and a stable internet network play an important role in the effectiveness of AR use [45]. In addition, adequate training for teachers to integrate AR in learning activities is also a key factor. Teachers who have a deep understanding of how to use this technology are likely to be able to utilize AR more effectively to increase student engagement [46].

The use of AR has a positive impact on students' learning motivation and academic results. The results of this research indicate that students who use AR show a higher increase in motivation compared to traditional learning methods. The interactive elements of AR help create a more engaging learning experience, which in turn encourages students to participate more and improve their learning outcomes [47]. Additionally, other studies also support these findings by showing that AR can increase knowledge retention due to a richer and more memorable learning experience [48].

Although AR has great potential in improving learning, there are several challenges faced in its implementation, especially in Indonesia. The main challenges include limited technological infrastructure, such as inadequate devices and internet connectivity in some areas [49]. Additionally, technical issues such as device compatibility and AR application quality can also hinder optimal use of this technology. Teachers and students need to adapt to these new technologies, and often require additional training to overcome technical difficulties that arise [50].

Perceptions of AR use are generally positive, both from teachers and students. Teachers feel helped by this technology, especially in explaining complex and abstract concepts through better visualization. Students, on the other hand, show high interest in using AR in other subjects because they feel that this technology enriches their learning experience. However, there are some teachers who feel that there is a need for more technical support and training to utilize this technology effectively in the context of online education.

V. Study Limitations

This study acknowledges potential teacher effects, as different instructors taught the experimental and control groups. Future research should control for instructor variables through crossover designs or teacher randomization.

VI. Conclusion

The results of this study indicate that the use of Augmented Reality (AR) in online learning at the elementary school level is associated with increased student engagement and improved academic performance. Specifically, the experimental group that received AR-supported instruction

showed a significant increase in average test scores, rising from 65.4 on the pre-test to 82.3 on the post-test, a gain of 16.9 points. In contrast, the control group, which followed traditional learning methods, demonstrated a smaller improvement of 3.7 points, with scores increasing from 64.8 to 68.5. This substantial difference suggests that AR's interactive and visual characteristics may facilitate a better understanding of complex concepts.

In addition, motivation questionnaire results revealed that students' interest and engagement grew after using AR, with average scores increasing from 3.2 to 4.5 on a 5-point scale. These findings imply that AR has the potential to support higher motivation in learning activities. Taken together, the evidence points to AR as a promising complementary tool to conventional online teaching methods, particularly when adequate technological resources and teacher preparedness are in place. Future studies should explore the long-term impact of AR integration on diverse learning styles and investigate its scalability across different educational contexts.

Ethical Statement

This study was conducted in accordance with the ethical guidelines for low-risk educational research of STIKOM Uyelindo Kupang Ethics Committee. Informed consent was obtained from all participants, and written parental consent was secured for minor participants.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Sumarlin Sumarlin: Conceptualisation, methodology, supervision, formal analysis, and writing; Yohanes Suban Belutowe: Methodology, software development, data curation, and investigation; Mardhalia Saitakela: Instrument development, validation, data curation, and investigation; Benyamin Jago Belalawe: Data collection and field investigation; Yosep Jacob Latuan: Data collection and qualitative analysis; Menya Snae: Quantitative and statistical analysis and visualization; Semlinda Juszandri Bulan: Validation and learning assessment development; Yohanis Malelak: Project administration, coordination, and resources; Hasibun Asikin: Supervision and technical and methodological review; and Sari Rahayu Rahman: Literature review and theoretical framework. All authors approved the final manuscript.

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