

RESEARCH ARTICLE

Augmented Reality to Enhance Informatics Learning Outcomes: A Quasi-Experimental Study in Vocational Education

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ABSTRACT

This study examines the effect of Augmented Reality (AR)-based learning media on Informatics learning outcomes at SMK Negeri 1 Bukittinggi, a vocational school recognized as a Centre of Excellence. Using a quasi-experimental pretest-posttest control group design, the study involved 70 tenth-grade students, divided into an experimental group (receiving AR-based learning media) and a control group (receiving traditional methods). The AR-based learning media focused on abstract Informatics concepts, such as algorithms and computer hardware, through interactive and immersive experiences. Results showed a significant improvement in the experimental group, with a mean post-test score difference of 7.31 points ($p < 0.001$). Statistical tests confirmed that the data met the assumptions of normality and homogeneity. Grounded in the cognitive theory of multimedia learning, the study highlights AR's potential to enhance engagement, comprehension, and knowledge retention by integrating theoretical and practical knowledge. Despite limitations, such as a focus on cognitive outcomes and reliance on technological infrastructure, the research highlights AR's transformative role in vocational education. Future studies should explore AR's scalability in under-resourced settings, its long-term effects, and its applicability across several disciplines.

KEYWORDS

Augmented reality; vocational education; student outcomes; educational technology

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1. INTRODUCTION

The 21st century has witnessed a rapid technological evolution, significantly transforming education through the widespread use of Information and Communication Technology (ICT). This digital

transformation has removed the boundaries of time and space, providing unprecedented access to learning opportunities [1], [2]. However, ensuring meaningful engagement and understanding among students in this technology-driven era remains an ongoing challenge, especially in vocational education environments that emphasize practical and technical skills [3], [4].

Vocational schools, particularly those designated as Centers of Excellence, face additional pressure to align their teaching methods with industry demands and equip students with practical skills relevant to the digital economy [5], [6]. At SMK Negeri 1 Bukittinggi, observations during the Educational Field Practice (PLK) from July to December 2023 indicated a critical gap in student learning outcomes in Informatics, a subject fundamental to modern engineering education. Despite using digital learning media such as e-books, videos, and PowerPoint presentations under the self-paced curriculum, only 62% of students achieved the minimum pass mark in the semester exams. These results highlight the limitations of existing digital learning media, which often fail to provide the interactivity and engagement required for effective learning [7].

The Informatics curriculum provides a unique challenge, requiring students to understand abstract concepts such as algorithms, data structures, and computer hardware. Innovative learning media beyond traditional methods is needed to overcome this challenge. Augmented Reality (AR) has emerged as a promising solution, offering interactive and immersive experiences by integrating real-world elements with virtual visualizations [8]. Unlike conventional media, AR-based learning media allows students to explore and manipulate complex concepts in real-time, improving understanding and retention [9]. For example, students can visualize how computers work or simulate algorithmic processes, bridging the gap between theory and practice [10]. Research indicates that AR-based learning media can improve student learning outcomes by up to 25%, thereby fostering engagement and motivation [11]–[13].

Despite its potential, the application of AR-based learning media in vocational education, particularly in Indonesia, remains underexplored. Most research focuses on general education settings, leaving a gap in understanding how AR-based learning media can address the unique challenges of vocational schools, such as limited technological infrastructure and a strong emphasis on practical skills [14]. This research aims to fill this gap by exploring the implementation of AR-based learning media in Informatics at SMK Negeri 1 Bukittinggi.

This research contributes theoretically by expanding the application of AR-based learning media in vocational education, overcoming the challenges of abstract concepts and limited student engagement. Practically, this research offers educators and policymakers valuable insights, providing a scalable, evidence-based model for integrating AR-based learning media into digital learning environments in vocational schools. As such, this research aims to improve student learning outcomes and advance the digital transformation of vocational education in Indonesia.

2. METHODS

2.1. Research Design

This study used a quantitative research approach with a quasi-experimental design, specifically a pretest-posttest control group design [15], [16], [17]. This design involves two groups: an experimental group that uses AR-based learning media and a control group that relies on traditional learning methods. The design is summarized in Table 1.

Table 1. Research design

Class	Pre-test	Treatment	Post-test
Experimental	O1	X	O2
Control	O3	-	O4

Where:

- O1 Pre-test for the experimental group
- O2 post-test of the experimental group after treatment
- O3 Pre-test for the control group
- O4 Post-test for the control group
- X Treatment was conducted over six sessions using AR-based learning media

The quasi-experimental design was chosen due to logistical constraints that prevented random assignment. Both groups were taught by the same teacher, using identical lesson plans and instructional materials, except for the AR-based intervention used in the experimental group [18]. This approach minimized potential confounding variables and ensured a controlled comparison between the two groups.

2.2. Research Setting and Participants

This research was conducted at SMK Negeri 1 Bukittinggi, a vocational school recognized as a Center of Excellence. The study involved 70 tenth-grade students, divided into two groups: experimental and control (35 students in each group). Participants were selected using purposive sampling to ensure comparability between groups. Selection criteria included gender balance, prior academic performance, and enrollment in the Informatics curriculum. These criteria minimized potential confounding variables and aligned with the study’s objectives.

To verify the initial equivalence of the groups, pre-test scores were analyzed, confirming that both groups had similar baseline abilities. This ensured that any observed differences in post-test scores could be attributed to the intervention rather than pre-existing disparities. The participant characteristics are summarized in Table 2 below:

Table 2. Participant characteristics

Variable		Experimental Group (n = 35)	Control Group (n = 35)	Total (n = 70)
Gender	Male	21 (60%)	22 (63%)	43 (61%)
	Female	14 (40%)	13 (37%)	27 (39%)
Age (years)	Mean	15.6	15.7	15.7
	Range	15–16	15–16	15–16
Pre-test	Mean Score	47.65	47.08	47.37
	Standard Deviation	(5.42)	(5.18)	(5.30)

2.3 Learning Media Development

The AR-based learning media used in this study were developed to support key Informatics concepts, such as algorithms and computer hardware. Unity software and the Vuforia SDK were utilized to create augmented reality visualizations [19], [20]. The media consisted of several components, including a main menu for navigation (Figure 1(a)), interactive displays of key hardware components such as the processor (Figure 1(b)), keyboard (Figure 1(c)), and motherboard (Figure 1(d)). Additional features included quiz questions for reinforcement (Figure 1(e)) and guided learning modules for exploration (Figure 1(f)).



Figure 1. The AR-based learning media: (a) Main Menu; (b) Processor AR display; (c) Keyboard AR display; (d) Motherboard AR display; (e) Quiz questions; and (f) Learning modules.

The AR-based learning media were validated by subject matter experts in Informatics and educational technology to ensure their usability and alignment with the curriculum. A pilot test was conducted with a small group of students to confirm the effectiveness of the media in addressing learning objectives. While this study utilized these tools, its primary focus was to evaluate the impact of AR on student learning outcomes rather than the development process.

2.4. Research Procedures

The research was conducted in three stages: the preparation stage, the implementation stage, and the reporting stage. Each stage is described in detail below.

2.4.1. Preparation Stage

The preparation stage involved several key activities to lay the groundwork for the study. Preliminary research was conducted to identify the research problem and establish the context of the study. This included discussions with teachers to align research objectives with practical classroom needs (Figure 2a). A research proposal detailing the objectives, methodology, and expected outcomes was drafted.

Research instruments, such as test grids and multiple-choice test questions, were developed to ensure they aligned with the Informatics learning objectives and competencies being studied. These instruments were refined through classroom activities, where feedback from teachers and students was gathered to enhance their relevance and usability (Figure 2b). Finally, a pilot test of the instruments was conducted with students with prior knowledge of the material to confirm their validity and reliability.

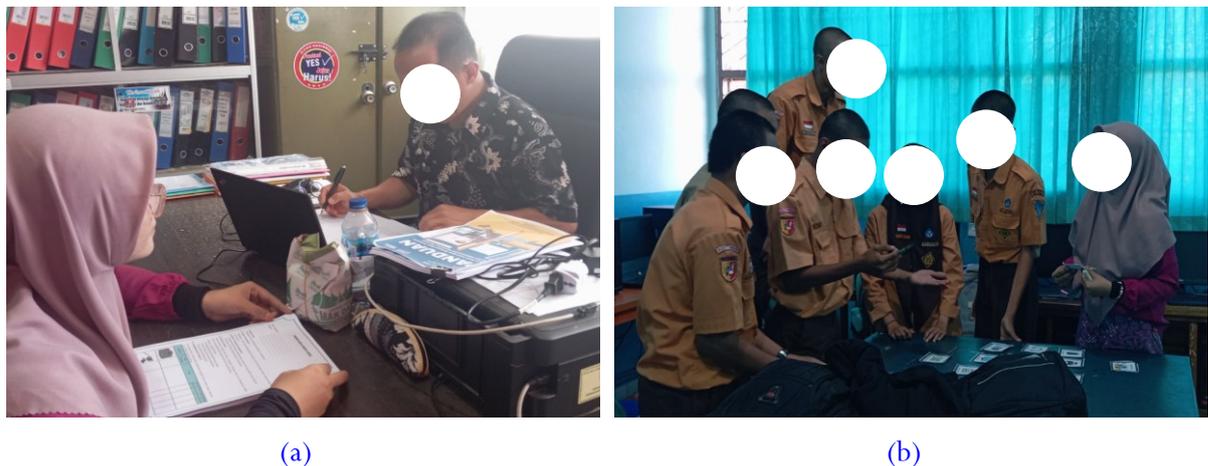


Figure 2. Preparation: (a) Discussion session with a teacher; (b) Classroom activity

2.4.2. Implementation Stage

The implementation stage commenced with the administration of a pre-test for both the experimental and control groups. This pre-test measured the students' baseline knowledge, allowing for a comparison of their initial abilities. The experimental group then engaged in a learning process utilizing AR-based learning media, which facilitated interactive and immersive experiences in exploring complex Informatics concepts. As illustrated in Figure 3a, students directly interacted with AR visualizations during the learning sessions, thereby enhancing their comprehension and engagement.

The AR-based learning media featured visualizations such as the VGA card, as shown in Figure 3b, which enabled students to explore its components and functionality in detail. Conversely, the control group followed traditional learning methods without the integration of AR. After completing the learning process, a post-test was administered to both groups to measure their learning outcomes and assess the impact of the AR-based intervention.



Figure 3. Implementation: (a) Students using AR-based media; (b) AR-based visualization of a VGA card

2.4.3. Reporting Stage

The collected data were processed and analyzed in the reporting stage using appropriate statistical methods to test the research hypotheses. Based on the analysis, conclusions were drawn regarding the effectiveness of AR-based learning media in improving learning outcomes, and the findings were compiled into the final research report.

2.5. Research Instruments

The data collection technique employed in this study was a test, which served as an assessment tool to measure students' learning outcomes [21]. This technique provided accurate information about students' initial abilities (pre-test) and final learning outcomes (post-test), aligning with the research objectives.

The research instrument consisted of multiple-choice tests divided into a pre-test and a post-test. The questions were carefully constructed based on a test grid aligned with the learning material and objectives to ensure their relevance to the expected competencies [22]. The pre-test was conducted before the experiment to assess the baseline abilities of the sample and confirm that both groups had comparable starting points [23]. The post-test was administered after the experimental treatment to measure the learning outcomes of the experimental and control groups.

Before implementation, the test items underwent rigorous analysis to ensure their validity, reliability, difficulty level and discriminating power. These steps were necessary to confirm that the questions accurately reflected students' abilities and aligned with the research goals.

2.5.1. Validity Test

Instrument validity was determined by assessing the accuracy and suitability of the test items as measurement tools. The validity of multiple-choice question items was analyzed using the point-biserial correlation coefficient (r_{bis}). According to the analysis, a test item was deemed invalid if the r_{bis} value was lower than the critical value specified in the correlation table [24], [25].

The validity test involved a trial with 26 participants, using 35 test items at a 5% significance level, resulting in a table correlation value of 0.388. The findings are as follows:

- a. For the pre-test, 25 items were valid, while 10 (ten) were invalid.
- b. For the post-test, 27 items were valid, while 8 (eight) were invalid.

Only the 25 valid items from the post-test were used in this study to ensure consistency and fairness. These validated questions were administered to both the experimental and control groups to measure students' abilities accurately.

2.5.2. Reliability Test

The reliability of the test refers to the instrument's consistency in measuring what it is intended to measure. It serves as an index that reflects the trustworthiness of a measuring tool [26]. An instrument is considered reliable if its reliability coefficient (r_{11}) exceeds the critical value (r_{table}). The formula (1) used for calculating reliability is as follows:

$$r_{11} = \left[\frac{k}{(k-1)} \right] \left[1 - \frac{\sum \alpha^2 b}{\alpha^2 t} \right] \tag{1}$$

Where:

r_{11}	Reliability coefficient
k	Number of question items
$\sum \alpha^2 b$	Sum of item variances
$\alpha^2 t$	Total score variance

1) Pre-test Reliability

Using the formula (1) above, the reliability of the pre-test questions was calculated as follows:

$$r_{11} = \left[\frac{25}{(25-1)} \right] \left[1 - \frac{4.86}{26.88} \right] = 0.853$$

2) Post-test Reliability

For the post-test questions, the reliability calculation is as follows:

$$r_{11} = \left[\frac{27}{(27-1)} \right] \left[1 - \frac{5.94}{38.27} \right] = 0.877$$

Based on the calculations of 25 questions declared valid in the pre-test and 27 post-test questions, there were a total of 52 questions. Using Microsoft Excel, the reliability test indicates that the pre-test instrument has a reliability value of 0.853, and the post-test has a reliability value of 0.877. Both values are higher than the r table at a significant level of 5% with $N = 26$, which is 0.3297. Thus, the pre-test and post-test instruments are declared reliable.

2.6 Data Collection

Data were collected during pre-tests and post-tests for the experimental and control groups. Observational notes and student feedback on the AR-based learning media were also gathered to provide qualitative insights. Pre-tests established baseline knowledge, while post-tests evaluated the effectiveness of the AR-based intervention.

2.7. Data Analysis Techniques

The data analysis in this experimental study utilized inferential statistical techniques, precisely a dependent samples T-Test, to compare the learning outcomes of the experimental group (using AR-based learning media) and the control group (using traditional methods). This technique was also applied to assess the same group's pre-test and post-test scores to evaluate the impact of the intervention [27]. The following steps outline the data analysis process employed in this study:

2.7.1. Normality Test

The normality of the data was assessed using the Kolmogorov-Smirnov test in SPSS, which evaluates whether the data distribution significantly deviates from normality. The observed statistic ("Kolmogorov-Smirnov Statistic" in SPSS) was compared to the critical value based on sample size and significance level, with results presented as a p-value. A p-value greater than 0.05 indicates that the data are typically distributed, while a p-value below 0.05 suggests non-normality [28]. Ensuring normality is critical for the validity of subsequent statistical analyses,

2.7.2. Homogeneity Test

The homogeneity of variance between the experimental and control groups was assessed using Levene's Test for Equality of Variances in SPSS. This test assesses whether the variances between groups are equal, a crucial assumption for conducting a t-test. A significance value (p-value) greater than 0.05 confirms homogeneity, indicating that the groups have comparable variability. Ensuring homogeneity is crucial to avoid biased results, as unequal variances could invalidate the t-test and lead to incorrect conclusions [29].

2.7.3. Hypothesis Testing

Hypothesis testing in this study was conducted using the Independent Samples T-Test in SPSS, comparing the post-test scores of the experimental and control groups. The null hypothesis (H_0) posited that there was no significant difference in learning outcomes between the two groups, while the alternative hypothesis (H_1) suggested a significant difference. Results were determined based on the p-value and the t-statistic. If the p-value (two-tailed) was less than 0.05, the null hypothesis was rejected, indicating a statistically significant difference in scores. The t-statistic was compared to the critical value at a significance level of 0.05 ($\alpha = 0.05$). If the calculated t-value (t-statistic) exceeded the critical value, H_0 was rejected in favor of H_1 [30]. These steps provided a robust evaluation of the impact of AR-based learning media on learning outcomes compared to traditional methods.

3. RESULTS

3.1. Descriptive Statistics

The learning outcomes for both groups were measured using pre-test and post-test scores, as shown in Table 3. The experimental group, which used AR-based learning media, achieved an average post-test score of 80.00 with a standard deviation of 9.16, while the control group, which relied on traditional methods, achieved an average post-test score of 72.69 with a standard deviation of 8.43. The pre-test scores for the experimental and control groups were 47.65 (SD = 5.42) and 47.08 (SD = 5.18), confirming comparable baseline abilities. The mean difference of 7.31 points in post-test scores

demonstrates a statistically significant improvement achieved by the experimental group, highlighting the effectiveness of AR-based learning media in enhancing learning outcomes.

Table 3. Tests of Normality

Group	N	Pre-test Mean (SD)	Post-test Mean (SD)
Experimental Group	35	47.65 (5.42)	80.00 (9.16)
Control Group	35	47.08 (5.18)	72.69 (8.43)

3.2. Assumption Testing

3.2.1. Normality Test

The normality test was conducted as a prerequisite for parametric statistical analysis, such as the t-test, which requires data to follow a normal distribution. This study employed two methods to evaluate the normality of the data: the Kolmogorov-Smirnov and Shapiro-Wilk tests. The Kolmogorov-Smirnov test is particularly suitable for larger sample sizes, while the Shapiro-Wilk test is more sensitive for smaller samples, providing a comprehensive evaluation of data distribution [31]. Table 4 summarizes the results of the normality tests for the pre-test and post-test scores of both groups:

Table 4. Tests of Normality

	Class	Kolmogorov-Smirnova			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
Learning Outcomes	Pre-Experiment	.118	35	.200*	.967	35	.376
	Pre-Control	.117	35	.200*	.947	35	.092
	Post-Experiment	.131	35	.135	.968	35	.388
	Post-Control	.132	35	.125	.944	35	.076

3.2.2. Homogeneity Test

The homogeneity test was conducted to verify whether the variances of the post-test scores between the experimental and control groups were equal. Homogeneity of variance is a critical assumption for parametric statistical tests, such as the independent samples t-test, to ensure the validity of the results. The test was performed using Levene’s test with SPSS, which calculates the significance value (Sig.) under different statistical approaches based on the mean, median, adjusted median, and trimmed mean. The results of Levene’s Test are presented in Table 5.

Table 5. Test of Homogeneity of Variance

		Levene Statistic	df1	df2	Sig.
Learning Outcomes	Based on the Mean	.064	1	68	.801
	Based on the Median	.125	1	68	.724
	Based on the median and with adjusted df	.125	1	67.34	.724
	Based on the trimmed mean	.100	1	68	.752

The significance value (Sig.) in all approaches is more significant than 0.05, indicating that the variances of the post-test scores between the experimental and control groups are homogeneous. Specifically, based on the mean, the Sig. = 0.801, confirming that the assumption of homogeneity is satisfied. Additional approaches (median, adjusted median, and trimmed mean) also support the conclusion, with significance values of 0.724 and 0.752, respectively. The Levene's Test results confirm that the post-test variances for the experimental and control groups are homogeneous. As such, the assumption of homogeneity of variance is met, allowing parametric statistical analysis, such as the independent samples t-test, to proceed without concerns about variance differences between groups.

3.3. Inferential Statistics

3.3.1. Paired Samples T-Test (Within Groups)

A paired samples t-test was conducted to evaluate the effectiveness of AR-based learning media within the experimental group. This test compares the pre-test and post-test scores of the same group to determine whether the intervention (AR-based learning media) has a significant effect on learning outcomes. The following hypotheses were tested:

- Null Hypothesis (H_0): There is no significant difference between the pre-test and post-test scores of the experimental group.
- Alternative Hypothesis (H_1): There is a significant difference between the pre-test and post-test scores of the experimental group.

The results of the Paired Samples T-Test for the experimental group are summarized in [Table 6](#).

Table 6. Paired Samples T-Test Results for the Experimental Group

Statistic	Pre-test Mean (SD)	Post-test Mean (SD)	t-value	df	Sig. (2-tailed)
Experimental Group	47.65 (5.42)	80.00 (9.16)	15.92	34	<0.001

The mean score of the experimental group increased from 47.65 (SD = 5.42) in the pre-test to 80.00 (SD = 9.16) in the post-test. The t-value of 15.92 with a p-value < 0.001 indicates that the difference between pre-test and post-test scores is statistically significant at the 0.05 level. This result supports the Alternative Hypothesis (H_1), confirming that the AR-based learning media significantly improved student learning outcomes within the experimental group.

3.3.2. Independent Samples T-Test (Between Groups)

The Independent Samples T-Test was conducted to compare the post-test scores of the experimental group (using AR-based learning media) and the control group (using traditional methods). This test aimed to determine whether the intervention (AR-based learning media) led to a statistically significant improvement in learning outcomes. The results, including the mean difference, t-value, and p-value, are summarized in [Table 7](#).

Based on [Table 7](#), Levene's Test for Equality of Variances yielded a significance value of 0.801 (greater than 0.05), confirming that the variances between the experimental and control groups were homogeneous. Therefore, the row labelled "Equal variances assumed" was used to interpret the t-test results.

Table 7. Independent Samples Test

Learning Outcomes	Levene's Test for Equality of Variances		T-Test for Equality of Means						
	F	Sig.	t	df	Sig. (2-tailed)	Mean Dif.	Std. Error Difference	95% Confidence Interval of the Difference	
								Lower	Upper
Equal variances assumed	.064	.801	3.478	68	.001	7.314	2.103	3.11	11.51
Equal variances are not assumed.			3.478	67.54	.001	7.314	2.103	3.11	11.51

The t-test results revealed the following:

- The t-value = 3.478 with df = 68 and p = 0.001, which is less than 0.05. This indicates that the null hypothesis (H_0) is rejected, and the alternative hypothesis (H_1) is accepted.
- The Mean Difference of 7.314 suggests that the experimental group scored, on average, 7.314 points higher than the control group.
- The 95% confidence interval for the mean difference ranged from 3.11 to 11.51, further confirming the significance of the difference.

The Independent Samples T-Test results demonstrate a statistically significant difference in post-test scores between the experimental and control groups. The experimental group, which utilized AR-based learning media, achieved a higher mean post-test score ($M = 80.00$, $SD = 9.16$) than the control group ($M = 72.69$, $SD = 8.43$). These findings indicate that AR-based learning media significantly improved learning outcomes in the experimental group compared to traditional teaching methods.

4. DISCUSSION

This study investigated the effectiveness of AR-based learning media in improving students' learning outcomes in Informatics at SMK Negeri 1 Bukittinggi. The findings provide compelling evidence that AR enhances student comprehension and engagement compared to traditional teaching methods. This section discusses the key findings in the context of existing literature, critically evaluates their implications, and highlights areas for further exploration.

4.1. Enhanced Learning Outcomes

The experimental group, which utilized AR-based learning media, demonstrated a significant improvement in post-test scores compared to the control group, with a mean difference of 7.31 points ($p < 0.001$). This suggests that AR-based media offer a more effective learning environment for vocational education. These findings align with prior studies that have reported improved engagement and comprehension through AR, particularly in technical subjects that require abstract reasoning [31].

However, the results also raise questions about the scalability of AR implementation in schools with limited technological infrastructure. While the controlled setting of this study ensures reliability, future research should explore the feasibility of deploying AR in diverse educational contexts, particularly in under-resourced schools.

4.2. Impact of AR on Abstract Concepts

One of the key challenges in teaching Informatics lies in its abstract topics, such as algorithms and computer architecture. AR-based media have shown potential in bridging this gap by providing interactive and immersive visualizations that transform theoretical concepts into tangible learning experiences. For instance, students could explore processor functionalities or motherboard configurations in real-time, fostering a deeper understanding.

These findings support the cognitive theory of multimedia learning, highlighting the importance of interactive tools in enhancing cognitive processes [32]. However, the effectiveness of AR may also depend on the quality of instructional design and teachers' ability to integrate these tools effectively. Poorly designed AR experiences or inadequate teacher training could diminish the potential benefits.

4.3. Motivation and Engagement

The study also highlighted increased motivation and engagement in the experimental group, consistent with previous research indicating that AR enhances learner interest by combining real-world and virtual elements [33]. Features like gamification (e.g., quizzes and interactive modules) likely contributed to this motivation, making learning more enjoyable and interactive.

However, it is worth noting that the novelty of AR might have played a role in boosting student interest. Long-term studies are necessary to determine whether these motivational effects persist once the novelty wears off. Additionally, future research should investigate whether AR can promote self-directed learning habits and critical thinking skills over time.

4.4. Statistical Validity and Robustness

The statistical tests confirmed that the data met the assumptions of normality and homogeneity, validating the use of parametric analyses such as t-tests. These results reinforce the robustness of the research design and highlight the importance of methodological rigor in educational research. The controlled environment, where both groups were taught by the same teacher using identical lesson plans (except for the AR intervention), minimized confounding variables. However, this also limits the study's generalizability to less controlled settings, such as classrooms with varying teaching styles or resources.

4.5. Practical Implications

The results of this study have several practical implications for educators and policymakers:

- 1) AR-based media can be incorporated into Informatics curricula to improve understanding of abstract concepts, particularly in vocational schools aiming to align with industry demands.
- 2) Effective AR implementation requires teachers to be adequately trained to integrate this technology into their teaching practices.

- 3) While this study demonstrated the effectiveness of AR in a controlled setting, future efforts should explore its scalability in diverse

5. CONCLUSION

This study highlights the significant potential of Augmented Reality (AR)-based learning media in improving students' learning outcomes in Informatics, particularly in vocational education. The experimental group achieved a statistically significant improvement in post-test scores compared to the control group, with a mean difference of 7.31 points ($p < 0.001$). This demonstrates AR's capability to address challenges in teaching abstract concepts, such as algorithms and computer hardware, by providing interactive and immersive learning experiences.

The findings align with the cognitive theory of multimedia learning, highlighting the importance of interactivity and visualization in enhancing comprehension and retention. These results suggest that AR-based learning media can be a transformative tool in vocational education, bridging the gap between theoretical knowledge and practical understanding. Furthermore, student feedback highlights increased motivation and engagement, reinforcing the quantitative results.

Despite these promising findings, the study has limitations. The small sample size and focus on cognitive outcomes limit the generalizability of the results. Additionally, the reliance on technological infrastructure presents challenges for scalability, particularly in under-resourced schools. Future research should explore the feasibility of AR in diverse educational settings, evaluate its long-term impacts on learning retention, and investigate affective and psychomotor outcomes, such as critical thinking skills and hands-on technical abilities.

Educators and policymakers must address barriers, such as teacher training and access to technology, to ensure the sustainable adoption of AR-based media. By integrating AR into curricula and providing adequate resources, vocational schools can better align with industry demands and prepare students for the digital economy. These efforts will help realize AR's full potential in transforming technical education.

DECLARATIONS

Author Contributions

Silvani Ilhani Fahira: Conceptualization, Methodology, Formal Analysis, Investigation, Software, Data curation, Writing - Original Draft. **Ika Parma Dewi:** Validation. **Ahmad Samed Al-Adwan:** Validation, Writing - Review & Editing. **Richelle C. Castro:** Writing - Review & Editing. All authors have read and approved the final version of this manuscript.

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Competing Interests

The authors declare no competing interests.

Generative AI and AI-Assisted Technologies Statement

During the preparation of this work, the author(s) used [DeepL](#) to improve the manuscript's readability, language, and overall structure. Following the use of this tool, the author(s) thoroughly reviewed and edited the content, ensuring its accuracy and integrity. The author(s) take full responsibility for the content and conclusions presented in the published article.

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