Jurnal Inovasi Teknologi Pendidikan
Volume 12, No. 2, June 2025 (179-191)
Online: http://journal.uny.ac.id/index.php/jitp

The effectiveness of augmented reality in enhancing learning outcomes in a microcontroller course

Mukhlisin [1] *, Andi Asrifan [1], Luís Miguel Oliveira de Barros Cardoso [2]
[1] Universitas Negeri Makassar, Indonesia.
[2] Polytechnic Institute of Portalegre, Portugal.
***** Corresponding Author. E-mail: mukhlisin@unm.ac.id

ARTICLE INFO

Article History
Received:
14 June 2025;
Revised:
5 July 2025;
Accepted:
6 July 2025;
Available online:
30 June 2025.

Keywords
Augmented reality (AR); Educational technology; Experimental design; Microcontroller course

ABSTRACT

One significant challenge in technical and vocational education is students' difficulty in achieving a deep conceptual understanding, particularly in complex subjects such as microcontrollers. Traditional methods often lack interactivity and real-world context, leading to low engagement and learning outcomes. Augmented Reality (AR) provides an immersive and interactive learning experience that enables students to visualize abstract concepts. This study examined the impact of AR-based instructional media on learning outcomes in a Microcontroller course, using a true experimental design (Solomon Four Group Design). Four student groups from four vocational higher education institutions in Makassar participated (total N = 143). Two groups received AR-based instruction, and two received conventional teaching; two of the groups also completed a pretest. Learning outcomes were assessed through essay-format pretests and posttests aligned with microcontroller learning indicators. Learning improvement was measured using normalized gain scores, and data were analyzed with normality tests, homogeneity tests, ANCOVA, independent t-tests, and N-Gain analysis. Results showed that AR significantly improved learning outcomes, with experimental groups achieving a mean gain score of 0.75 (in the high category), compared to 0.16 (in the low category) in control groups. Statistical tests confirmed significant differences between groups ($p < 0.05$), while comparisons among control groups indicated no substantial pretest effect. This confirms that the learning improvement resulted from the AR intervention. The findings suggest AR-based instructional media effectively enhance conceptual understanding, learning quality, and student engagement in technical education. The study concludes that AR is a viable instructional tool in vocational learning and recommends its broader use and further development in similar educational contexts.

How to cite:
Mukhlisin., Asrifan, A., & Cardoso, L. M. O. D. B. (2025). The effectiveness of augmented reality in enhancing learning outcomes in a microcontroller course. *Jurnal Inovasi Teknologi Pendidikan*, *12*(2), 179-191. https://doi.org/10.21831/jitp.v12i2.86903

INTRODUCTION

The rapid advancement of digital technology has driven significant transformations in the field of education, particularly in teaching and learning methods within technical and vocational domains. One of the major challenges in vocational education lies in effectively delivering complex technical concepts in a manner that is accessible and comprehensible to students, especially in courses such as

Microcontrollers. Conventional instructional approaches often fall short in facilitating deep conceptual understanding due to limitations in visualization and interactivity.

The advancement of digital technology in education has created significant opportunities to transform classroom learning experiences (Mahendru et al., 2024). Despite these developments, the instructional practices in many educational institutions remain predominantly conventional, characterized by teacher-centered approaches and the use of static instructional media such as textbooks and whiteboards (Koumpouros, 2024). This dependency on traditional methods often results in passive, non-interactive, and decontextualized learning environments, which in turn lead to low student motivation and limited conceptual understanding, particularly in science, technology, engineering, and mathematics (STEM) related disciplines (Tiwari et al., 2024).

A fundamental issue within conventional instruction lies in the inability of traditional media to effectively represent abstract or complex concepts visually and interactively (Quang & Duc, 2023). Concepts such as molecular structures, mechanical systems, human anatomy, and natural phenomena are often challenging to comprehend through verbal explanation or two-dimensional illustrations alone (Naithani & Guleria, 2024). Consequently, students struggle to develop comprehensive conceptual frameworks and are susceptible to learning loss, especially when dealing with spatially demanding content that requires advanced visual imagination (González et al., 2025).

Simultaneously, the current generation of learners, commonly referred to as digital natives, demonstrates learning preferences that are markedly different from those of previous generations (Zhao et al., 2025). They are more engaged with learning environments that are digital, visual, interactive, and technologically enriched. Unfortunately, many instructional systems in schools and universities have not adequately adapted to these evolving learner characteristics (Kiesler et al., 2025). This misalignment has created a pedagogical gap between students' learning styles and the teaching approaches commonly employed, thereby intensifying the need for innovative learning strategies that bridge this divide (Zou et al., 2025). Digital technology, in this context, offers motivational appeal and captures the interest of young learners through various digital platforms and multimedia content (Efremova & Huseynova, 2021).

In response to these challenges, Augmented Reality (AR) has emerged as a promising instructional innovation (Turkcan et al, 2023). AR enables the real-time integration of digital content into the physical environment, creating immersive, interactive, and contextualized learning experiences (Tatić & Tešić, 2017). Through AR, students can directly engage with 3D models, simulations, and dynamic information that enhance the exploration and understanding of concepts more practically and visually. Empirical studies have consistently reported that AR-based learning significantly enhances student motivation, active participation, and conceptual comprehension when compared to traditional media (Singh & Ahmad, 2024).

Despite the promising potential of AR in education, there remains a notable gap in rigorous empirical research examining its effectiveness, especially within the context of formal education settings (Laumann et al., 2024). Much of the existing literature is descriptive or limited to single-group experimental designs, thus lacking robust evidence of AR's impact when compared through more methodologically sound frameworks (López-Bouzas et al., 2024). To validate that improvements in learning outcomes are a result of AR and not merely due to novelty effects or participant expectancy, a more comprehensive and controlled research design is required (Chen et al., 2024).

To address this methodological gap, this study employed the Solomon Four Group Design, an experimental approach widely regarded as rigorous and capable of controlling for pretest effects and other external threats to validity (Covvey et al., 2023). This design not only measures the impact of AR on learning outcomes but also examines whether the administration of a pretest influences those outcomes (Mokmin et al., 2023). Ensuring such internal validity is essential for generating reliable findings that can inform educational policy and guide the development of AR-based learning models in the future (Chang et al., 2022; Jičínská et al., 2021).

This study addresses the pressing need for adaptive, learner-centered, and technology-integrated instructional innovations that align with the characteristics of contemporary vocational learners. Augmented Reality (AR) is positioned not merely as a technological novelty but as a strategic pedagogical tool capable of addressing the limitations of traditional instructional methods by enhancing interactivity, visualization, and learner engagement. The primary aim of this research is to examine the effect of AR-based instructional media on student learning outcomes in the Microcontroller course within vocational higher education. Utilizing a true experimental design with the Solomon Four Group Design, the study provides robust empirical evidence on the efficacy of AR in fostering conceptual understanding in technical education. The significance of this study lies in its threefold contribution: (1) offering empirical data on the pedagogical impact of AR in vocational education, where such studies remain limited; (2) presenting a replicable instructional model for integrating AR into microcontroller instruction; and (3) informing educators, curriculum developers, and policymakers on the potential of immersive learning technologies to enhance learning effectiveness and student engagement. As such, this research contributes both to the theoretical discourse on educational technology and to practical improvements in vocational teaching practices.

METHOD

This study employed a true experimental design using the Solomon Four Group Design model, which consists of four student groups with different combinations of pretest and treatment. This design enables the researcher to objectively measure the effect of using AR media on student learning outcomes while eliminating potential testing bias (i.e., the influence of the pretest on posttest performance). The study was conducted across four polytechnic institutions, involving second-semester students enrolled in the microcontroller course.

Table 1. Model of the Solomon Four Group Design

No.	Group	Pretest	Treatment	Posttest	Polytechnic	Students
1	Experiment 1	O_1	X_1	O_2	Polytechnic A	37
2	Control 1	O_3		O_4	Polytechnic B	35
3	Experiment 2		X_2	O_5	Polytechnic C	36
4	Control 2			O_6	Polytechnic D	35
Total						**143**

Description:
O_1 = Pretest Experiment 1
O_2 = Posttest Experiment 1
O_3 = Pretest Control 1
O_4 = Posttest Control 1
O_5 = Posttest Experiment 2
O_6 = Posttest Control 2
X_1 = Treatment Experiment 1
X_2 = Treatment Experiment 2

Experimental Group 1 and Control Group 1 received a pretest, while Experimental Group 2 and Control Group 2 did not. Both Experimental Groups 1 and 2 received treatment in the form of learning using AR-based instructional media, whereas Control Groups 1 and 2 underwent conventional learning as previously implemented. The data collection technique in this study focused on measuring students' learning outcomes through a series of tests designed to assess conceptual understanding and applied skills in the Microcontroller course. The primary instrument used was an essay-type test, developed based on learning outcome indicators and a blueprint of core microcontroller topics. The test items were constructed to evaluate students' abilities in analyzing, synthesizing, and applying concepts and the working principles of microcontroller systems in various technical contexts.

Table 2. Microcontroller Knowledge Test Instrument

No.	Intrument Test	Indicator
1	Explain the fundamental differences between a microcontroller and a microprocessor.	C2 – Understanding
2	Describe the main components found in the architecture of a microcontroller.	C2 – Understanding

No.	Intrument Test	Indicator
3	Illustrate and explain the working principle of the input-output (I/O) system in a microcontroller.	C3 – Applying
4	Explain the working process of the Analog to Digital Converter (ADC) in a microcontroller.	C2 – Understanding
5	Write and explain the steps for programming a microcontroller to make an LED blink every 1 second using the C programming language.	C3 – Applying
6	Analyze the differences between serial and parallel communication in microcontrollers.	C4 – Analyzing
7	Explain the concept of interrupts in microcontrollers and provide an example of its application in a sensor-based system.	C4 – Analyzing
8	A microcontroller system uses a temperature sensor to automatically activate a fan. Create a logic flow (flowchart or narrative explanation) that describes the process.	C5 – Creating
9	Describe the steps for connecting a microcontroller to a 16x2 LCD module. Explain how data is displayed on the screen.	C3 – Applying
10	In an automatic control system project based on a microcontroller, how do you determine the appropriate type of microcontroller? State the technical criteria that should be considered and justify your choices.	C6 - Evaluating

The data obtained were analyzed using several statistical techniques, namely: (1) Analysis of Covariance (ANCOVA) – This was used to examine the effect of AR-based learning treatment on posttest scores while controlling for pretest scores as a covariate. The purpose was to determine the pure effect of Augmented Reality on learning outcomes after accounting for initial differences in student ability; (2) Independent Samples t-Test – this test was conducted to compare learning outcomes between groups to assess the statistical significance of differences between the experimental and control groups on the posttest. It was also used to detect whether the pretest had any effect on posttest results; and (3) N-Gain Score Analysis - this analysis was employed to measure the improvement in students' learning outcomes by comparing pretest and posttest scores in the groups that received the treatment.

$$\text{N-Gain Score} = \frac{\text{Postest Score} - \text{Pretest Score}}{\text{Score Max} - \text{Pretest Score}} \quad (1)$$

The N-Gain results were classified into three categories: high (> 0.7), medium (0.3–0.7), and low (< 0.3). Before analysis, the data were tested for assumptions of normality using the Kolmogorov-Smirnov test and for homogeneity of variances using Levene's Test to ensure that the data met the requirements for parametric statistical analysis.

Table 3. Categorization of Normalized Gain Score (N-Gain)

No.	N-Gain Coefficient	Category
1.	$n > 0.7$	High
2.	$0.3 \leq n \leq 0.7$	Medium
3.	$n < 0.3$	Low

(Leny et al., 2024)

RESULTS AND DISCUSSION

Results

This study employed the Solomon Four Group Design, an experimental method involving four groups to measure the effect of a treatment while controlling for potential pretest effects. The design consisted of two experimental groups that received instruction using AR and two control groups that underwent conventional instruction without AR. Experimental Group 1 and Control Group 1 were administered a pretest, whereas Experimental Group 2 and Control Group 2 were not. The instructional approach for the experimental groups was designed to be interactive, utilizing AR media to explain key concepts in the Microcontroller course. In contrast, the control groups were taught using traditional lecture methods and static media such as presentation slides and whiteboards. Following the intervention, all groups were given a posttest in the form of essay-based assessments to evaluate learning outcomes. Figure 1 presents the average learning outcomes across the four groups, serving as the basis for evaluating the effectiveness of AR integration in technical vocational education.

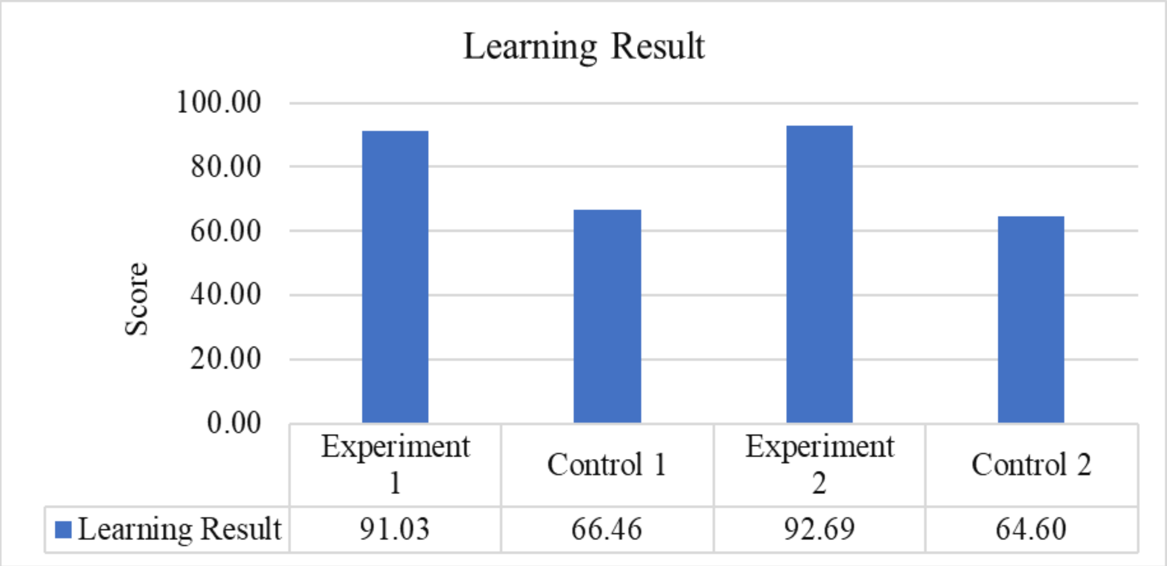

Figure 1. Average Learning Outcomes in the Microcontroller Course

Based on the Learning Result graph presented, there is a notable difference in learning outcomes between students in the experimental groups and those in the control groups. Experimental Group 1, which received AR-based instruction and a pretest, achieved an average score of 91.03. Meanwhile, Experimental Group 2, which also received AR-based instruction but without a pretest, recorded a slightly higher average score of 92.69. These results indicate that AR-based learning consistently has a positive impact on student performance, regardless of the presence or absence of a pretest.

In contrast, Control Group 1, which underwent conventional instruction with a pretest, achieved an average score of 66.46, while Control Group 2, which received neither a pretest nor AR-based instruction, obtained an average score of 64.60. These values are significantly lower than those of the experimental groups, suggesting that traditional instructional methods are less effective in fostering a deep conceptual understanding of microcontroller content.

The differences in scores between the experimental and control groups demonstrate that the use of AR media significantly enhances student learning outcomes and that the pretest itself does not exert a meaningful influence on final performance. This reinforces the conclusion that the observed improvement in learning is primarily attributable to the integration of AR as an interactive instructional tool, rather than to repeated exposure to test content. Thus, the findings support the effectiveness of AR technology as an innovative solution in education, particularly in the context of technical learning.

Normality Test of the Data

In this study, the normality test was conducted to ensure that the pretest and posttest scores in each group met the assumption of normal distribution. The One-Sample Kolmogorov-Smirnov Test was employed, which is a commonly used statistical test to determine whether the distribution of a sample significantly deviates from a normal distribution. The results of this test served as the basis for determining whether subsequent data analysis could be carried out using parametric statistical techniques or whether non-parametric alternatives would be required. The results of the normality test are presented in Table 4.

Table 4. Normality Test Results for Experimental Group 1 and Control Group 1

		Pretest Experiment 1	**Posttest Experiment 1**	**Pretest Control 1**	**Posttest Control 1**
N		37	37	35	35
Normal Parameters[a,b]	Mean	63.6486	91.0270	63.0857	66.4571
	Std. Deviation	4.04294	4.27191	3.95840	4.75483
Most Extreme Differences	Absolute	.126	.135	.143	.140
	Positive	.126	.083	.114	.140
	Negative	-.125	-.135	-.143	-.126
Test Statistic		.126	.135	.143	.140
Asymp. Sig. (2-tailed)		.147[c]	.088[c]	.068[c]	.079[c]

Table 5. Normality Test Results for Experimental Group 2 and Control Group 2

		Posttest Experiment 2	**Posttest Control 2**
N		36	35
Normal Parameters[a,b]	Mean	92.6944	64.6000
	Std. Deviation	3.90472	4.62856
Most Extreme Differences	Absolute	.131	.131
	Positive	.107	.131
	Negative	-.131	-.077
Test Statistic		.131	.131
Asymp. Sig. (2-tailed)		.123[c]	.138[c]

Based on the results of the normality test analysis using the One-Sample Kolmogorov-Smirnov Test, it was found that the data from all research groups met the assumption of normal distribution. This test was conducted to ensure that the data from each group intended for analysis using parametric statistical techniques conformed to a reasonable distribution, thereby allowing for valid interpretation of the results. For Experimental Group 1, the significance value for the pretest was 0.147, and for the posttest, it was 0.088. Both values exceed the critical threshold of 0.05, indicating that the data for both pretest and posttest in this group are normally distributed. Similarly, in Control Group 1, the pretest yielded a significance value of 0.068, and the posttest yielded 0.079—both above the 0.05 threshold, suggesting that the data in this control group also meet the normality assumption. Furthermore, for Experimental Group 2 (which did not receive a pretest but was given the AR-based treatment), the posttest produced a significance value of 0.123, and in Control Group 2, the posttest yielded 0.138. As with the previous groups, these values indicate that the data in both groups are normally distributed.

Accordingly, for all six datasets tested, Pretest Experimental Group 1, Posttest Experimental Group 1, Pretest Control Group 1, Posttest Control Group 1, Posttest Experimental Group 2, and Posttest Control Group 2, the significance values were all greater than 0.05. This confirms that there were no significant deviations from normal distribution across any of the groups. Therefore, the assumption of normality is fulfilled, meaning that the data may be further analyzed using parametric statistical techniques such as ANCOVA, the Independent Samples t-test, and N-Gain Score analysis to assess the improvement in learning outcomes. Meeting this assumption is essential to ensure that interpretations regarding the effect of AR-based instruction in the Microcontroller course are scientifically accurate and defensible.

Homogeneity Test

After the normality test was conducted and the data were confirmed to follow a normal distribution, the next step before performing parametric statistical analysis was to examine the homogeneity of variances. The purpose of this test is to determine whether the variances or the spread of data across the groups being compared are statistically equivalent. The homogeneity of variance was assessed using Levene's Test, which identifies whether there are significant differences in variance among the groups. If the significance value (Sig.) exceeds 0.05, the variances are considered homogeneous, and the assumption of homogeneity is deemed to be met. The results of the homogeneity test are presented in Table 6.

Table 6. Results of the Homogeneity Test

Levene Statistic	df1	df2	Sig.
.295	3	139	.829

Based on the results of the homogeneity of variance test using Levene's Test, as presented in the table, a significance value (Sig.) of 0.829 was obtained. This value is substantially higher than the critical threshold of 0.05, indicating that there is no significant difference in variance among the groups compared in this study. Therefore, it can be concluded that the learning outcome data across the four groups exhibit homogeneous or equal variances. Homogeneity of variance is a fundamental assumption that must be met before performing parametric statistical analyses such as ANCOVA or the Independent Samples t-test. When this assumption is satisfied, the results of inferential analyses are considered more valid and unbiased, as the equal distribution of data across groups ensures the integrity of statistical comparisons. Based on the results of Levene's Test, further analysis may proceed using parametric statistical approaches, as both the normality and homogeneity assumptions have been statistically satisfied. This strengthens the validity of hypothesis testing regarding the impact of using AR media in the teaching of the Microcontroller course.

ANCOVA Analysis

In this study, Analysis of Covariance (ANCOVA) was employed to compare the posttest scores between the experimental groups, which utilized Augmented Reality (AR) media, and the control groups, which received instruction through conventional teaching methods, while controlling for pretest scores as a covariate. Accordingly, ANCOVA not only measures the differences in learning outcomes between groups but also ensures that these differences are not attributable to variations in prior knowledge or initial ability, but rather to the treatment administered during the learning process. The results of the ANCOVA analysis are presented in Table 7.

Table 7. ANCOVA Analysis Results

No.	Source	Type III Sum of Squares	df	Mean Square	F	Sig.
1	Corrected Model	11245.593[a]	2	5622.796	525.972	.000
2	Intercept	219.035	1	219.035	20.489	.000
3	Pretest	704.436	1	704.436	65.895	.000
4	Model	10003.233	1	10003.233	935.730	.000
5	Error	716.250	67	10.690		
Total		**445835.000**	**70**			
Corrected Total		**11961.843**	**69**			

Based on Table 7, which presents the results of the ANCOVA analysis on the posttest as the dependent variable, it was found that there is a statistically significant effect of the independent variable on students' learning outcomes after controlling for pretest scores. The F-value for the model variable was 935.730, with a significance level (Sig.) of 0.000. This value is well below the critical threshold of 0.05, indicating that the instructional model had a highly significant effect on posttest performance. In other words, the use of AR-based instructional media made a substantial and meaningful contribution to improving student learning outcomes in the Microcontroller course.

Thus, the results of the ANCOVA provide strong evidence that AR-based learning is significantly more effective than conventional instruction in improving student learning outcomes, even after controlling for prior ability. These findings support the notion that the integration of Augmented Reality technology in vocational education, particularly in the Microcontroller course, can yield both statistically and practically significant impacts on student achievement.

Independent Sample t-test Analysis

This test was employed to determine whether there is a statistically significant difference in learning outcomes between two independent groups, namely the experimental group and the control group. The results of the Independent Samples t-Test are presented in Table 8.

Table 8. Results of the Independent Samples t-Test Analysis

t-test for Equality of Means						
T	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
					Lower	Upper
27.67	69	.000	28.09	1.015	26.06	30.11
27.60	66.43	.000	28.09	1.017	26.06	30.12

Based on Table 8, which presents the results of the Independent Samples t-Test analysis, it was found that there is a highly significant difference between the two groups being compared in terms of their mean learning outcomes. The t-value was 27.67 with 69 degrees of freedom (df), yielding a two-tailed significance value (Sig.) of 0.000. This value is well below the significance threshold of 0.05, indicating that the difference in mean scores between the two groups is statistically significant. Overall, these findings suggest that the group receiving the treatment (e.g., the use of AR-based instructional media or another targeted intervention) achieved significantly higher learning outcomes than the group that did not receive the intervention. This indicates that the instructional intervention had a positive and effective impact on improving students' academic performance.

Pretest Effect Analysis

To determine whether the pretest affected learning outcomes, a comparison was conducted between Control Group 1 (which received a pretest) and Control Group 2 (which did not receive a pretest). Both groups were taught using conventional instructional methods and did not receive the AR-based learning intervention. The results of the pretest effect analysis are presented in Table 9.

Table 9. Results of the Pretest Effect Analysis

t-test for Equality of Means						
T	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
					Lower	Upper
1.65	68	.102	1.85	1.12	-.38	4.09
1.65	67.95	.102	1.85	1.12	-.38	4.09

Based on Table 9, which presents the results of the pretest effect analysis between Control Group 1 and Control Group 2, the t-value was found to be 1.65 with 68 degrees of freedom (df), and a two-tailed significance value (Sig.) of 0.102. Since this value is greater than the significance threshold of 0.05, it can be concluded that there is no statistically significant difference between the two control groups. This result indicates that administering a pretest did not have a significant effect on the learning outcomes of students who did not receive the instructional intervention. In other words, the presence of the pretest did not meaningfully influence student performance on the posttest, suggesting that no significant pretest effect occurred within the control condition. This finding is particularly important as it supports the assumption that any differences in learning outcomes observed in the experimental groups can be attributed to the treatment (e.g., the use of AR) rather than to the influence of the pretest. Consequently, it reinforces the internal validity of the Solomon Four Group Design employed in this study.

Normalized Gain Score Analysis

Table 10. Results of the N-Gain Score Analysis

No.	Group	Mean Pretest	Mean Posttest	Mean Gain Score
1	Experiment 1	63.46	91.02	0.75
2	Control 1	63.08	66.45	0.16

Based on Table 10, which presents the comparative results of the mean pretest, posttest, and gain scores between Experimental Group 1 and Control Group 1, a substantial difference in learning improvement was observed. Experimental Group 1, which received AR-based instruction, had a mean pretest score of 63.46, which increased significantly to 91.02 in the posttest. This improvement resulted in a mean gain score of 0.75, classified as high according to the normalized gain score criteria.

In contrast, Control Group 1, which received conventional instruction, recorded a mean pretest score of 63.08, with only a slight increase to 66.45 in the posttest. This yielded a mean gain score of 0.16, which falls into the low category (g < 0.3). These results indicate that although both groups began with relatively similar initial abilities, the group exposed to technology-enhanced learning demonstrated a significantly greater improvement in learning outcomes.

Therefore, the gain score data provide strong evidence that the integration of Augmented Reality (AR) into the learning process substantially enhances instructional effectiveness and students' conceptual understanding compared to traditional teaching methods. This finding reinforces the conclusion that the use of interactive digital technology not only boosts learning motivation but also leads to more optimal cognitive outcomes. The high gain score achieved by the experimental group serves as a clear indicator of the success of this innovative, technology-driven instructional intervention.

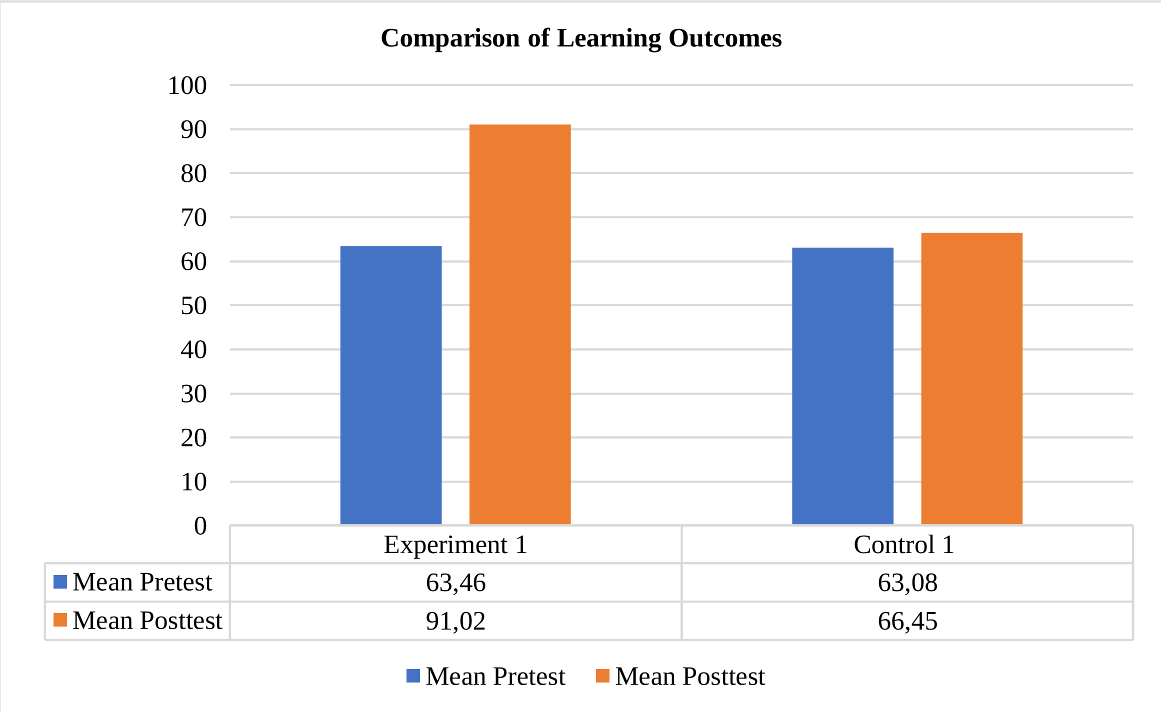

Figure 2. Comparison of Learning Outcomes Experimental 1 and Control 1

Discussion

This study addresses the issues and gaps identified in the background, namely the continued dominance of conventional teaching methods that are not adaptive to the learning characteristics of digital-native students, as well as the limitations of instructional media in presenting abstract concepts visually and interactively (Mukhlisin, et al., 2022). Through the integration of AR in the teaching of the Microcontroller course, the study demonstrates that AR can provide a more immersive and contextual learning experience, significantly enhancing students' learning outcomes (Palada et al., 2024). This is evidenced by the substantial difference in posttest scores between the experimental and control groups, with the experimental group achieving a normalized gain score of 0.75 (high category), compared to only 0.16 in the control group. These findings suggest that AR not only captures student attention but is also effective in deepening their conceptual understanding of complex technical content (Gargrish et al., 2021).

The rapid advancement of technology has brought significant changes to educational media, which were traditionally rooted in conventional methods but can now be implemented more practically using digital tools (Handani et al., 2020). Among the technologies gaining increasing attention in education is Augmented Reality (Alamsyah & Krisdiawan, 2021). AR represents a sophisticated paradigm of human-computer interaction, wherein three-dimensional virtual elements are seamlessly integrated with the user's perception of the real world, allowing for responsive and intuitive interaction (Mukhlisin et al., 2023; Mukhlisin et al., 2022).

Furthermore, by employing the Solomon Four Group Design, this study was able to confirm that the improvement in learning outcomes was not attributable to pretest effects, but rather resulted purely from the effectiveness of the AR-based learning media. This is supported by the lack of significant differences between Control Group 1 (with pretest) and Control Group 2 (without pretest), as well as the consistently high performance observed in both experimental groups, regardless of pretest administration (Lichtenberger et al., 2025). This design enhances the internal validity of the study and places the findings on solid ground to inform educational policy and the development of future digital learning models (Thohir et al., 2021).

The primary contribution of this research lies in providing robust empirical evidence that the use of AR significantly enhances learning effectiveness in vocational education, particularly in mastering science- and technology-based content (Jeffri & Rambli, 2021). Amid the growing demand for adaptive and contextual learning, this study offers a strategic solution through the implementation of digital technologies that align with the learning preferences of the current generation of students (Efremova & Huseynova, 2021). Moreover, the rigorous methodological approach adopted in this study contributes to the academic literature by addressing the existing gap in experimental research on AR within the context of formal education. Accordingly, these findings not only enrich the discourse on technology-enhanced learning but also provide a strong foundation for policy innovation and instructional practice in the digital era (Alonzo et al., 2024).

Through the outcomes of this research, the application of AR in education opens new opportunities to create more personalized and adaptive learning environments, where each student can learn at their own pace and according to their individual learning style (Namkoong et al., 2023). AR enables the embedding of virtual information into the physical world, displayed through devices such as computers and smartphones (Aditya et al., 2020). Consequently, the implementation of AR not only facilitates deeper conceptual understanding but also has the potential to foster intrinsic motivation and active student engagement in the learning process, ultimately leading to enhanced overall academic performance (Laumann et al., 2024).

CONCLUSION

Based on the findings of this study, which employed the Solomon Four Group Design, it can be concluded that AR-based instructional media has a significantly positive effect on students' learning outcomes in the Microcontroller course. The experimental groups that received AR-based learning interventions demonstrated higher improvements in learning outcomes compared to the control groups, as evidenced by both posttest scores and gain scores. The average gain score in the experimental groups reached 0.75, classified as high, while the control groups achieved only 0.16, categorized as low, despite having relatively equivalent baseline abilities. These results confirm that AR contributes substantially to enhancing the effectiveness of the learning process.

The use of AR has proven to be superior in presenting instructional content in a visual, interactive, and contextualized manner, effectively bridging abstract concepts and making them more accessible to learners. Moreover, the application of the Solomon Four Group Design provided strong methodological rigor in controlling for potential sources of bias, particularly the pretest effect. The finding that pretesting did not significantly influence learning outcomes strengthens the validity of the results and confirms that the observed improvements are due solely to the effectiveness of the AR-based intervention. Based on the findings of this study, it is recommended that future research be conducted to further explore the use of AR-based instructional media across a wider range of courses and areas of expertise within vocational education, to examine the consistency of its impact on student learning outcomes. Subsequent studies are also encouraged to integrate AR with active pedagogical approaches such as Problem-Based Learning (PBL), Project-Based Learning (PjBL), or flipped classroom models. Such integration would provide a more comprehensive understanding of the effectiveness of AR in fostering critical thinking, collaboration, and creativity skills among vocational learners.

REFERENCES

Aditya, I. P. T., Udayana, A. A. G. B., & Swandi, I. W. (2020). Perancangan media pembelajaran interaktif ensiklopedia Wayang kamasan berbasis augmented reality. *Amarasi Jurnal Desain Komunikasi Visual*, *1*(1), 9–21. https://doi.org/10.59997/amarasi.v1i01.32

Alamsyah, N., & Krisdiawan, R. A. (2021). Pembangunan aplikasi sebagai media pembelajaran bangun ruang tingkat SD/SMP dengan menggunakan metode marker augmented reality. *Nuansa Informatika*, *15*(1), 23-31. https://doi.org/10.25134/nuansa.v15i1.3847

Alonzo, D., Quimno, V., Townend, G., & Zin, C. (2024). Using information and communication technology (ICT)- based data systems to support teacher data - driven decision - making : Insights from the literature (2013 – 2023). *Educational Assessment, Evaluation and Accountability*, *36*(4), 433–451. https://doi.org/10.1007/s11092-024-09443-8

Chang, H., Binali, T., Liang, J., Chiou, G., Cheng, K., Lee, S. W., & Tsai, C. (2022). Ten years of augmented reality in education: A meta-analysis of (quasi-) experimental studies to investigate the impact. *Computers & Education*, *191*, 1-24. https://doi.org/10.1016/j.compedu.2022.104641

Chen, Y., Wang, X., Le, B., & Wang, L. (2024). Why people use augmented reality in heritage museums: A socio-technical perspective. *Heritage Science*, *12*(1), 1–19. https://doi.org/10.1186/s40494-024-01217-1

Covvey, J. R., McClendon, C., & Gionfriddo, M. R. (2023). Back to the basics: Guidance for formulating good research questions. *Research in Social and Administrative Pharmacy*, *20*(1), 66–69. https://doi.org/10.1016/j.sapharm.2023.09.009

Efremova, N., & Huseynova, A. (2021). The impact of digital technology on learning motivation and learning modes. *E3S Web of Conferences*, *273*, 1-5. https://doi.org/10.1051/e3sconf/202127312083

Gargrish, S., Kaur, D. P., Mantri, A., Singh, G., & Sharma, B. (2021). Measuring effectiveness of augmented reality-based geometry learning assistant on memory retention abilities of the students in 3D geometry. *Computer Applications in Engineering Education*, *29*(6), 1811–1824. https://doi.org/10.1002/cae.22424

González, E. M. D., Belaroussi, R., Soto-Martín, O., Acosta, M., & Martín-Gutiérrez, J. (2025). Effect of interactive virtual reality on the teaching of conceptual design in engineering and architecture fields. *Applied Sciences*, *15*(8), 1-23. https://doi.org/10.3390/app15084205

Handani, S. W., Hidayah, S. N., & Setiawan, I. (2020). Penilaian user experience menggunakan metode technology acceptance model (TAM) terhadap aplikasi augmented reality Gamelan Jawa. *JITU Journal Informatic Technology And Communication*, *4*(2), 1–10. https://doi.org/10.36596/jitu.v4i2.348

Jeffri, N. F. S., & Rambli, D. R A. (2021). A review of augmented reality systems and their effects on mental workload and task performance. *Heliyon*, *7*(3), 1-14. https://doi.org/10.1016/j.heliyon.2021.e06277

Jičínská, L., Sedláčková, P., Kolek, L., Tetourová, T., Volná, K., Lukavský, J., & Brom, C. (2021). Extrinsically integrated instructional Quizzes in learning games: An educational disaster or not? *Frontiers in Psychology*, *12*, 1-8. https://doi.org/10.3389/fpsyg.2021.678380

Kiesler, N., Smith, J. J. B., Leinonen, J., Fox, A., MacNeil, S., & Ihantola, P. (2025). The role of generative AI in software student CollaborAItion. *ArXiv (Cornell University)*, 1-7. https://doi.org/10.48550/arxiv.2501.14084

Koumpouros, Y. (2024). Revealing the true potential and prospects of augmented reality in education. *Smart Learning Environments*, *11*(2), 1-62. https://doi.org/10.1186/s40561-023-00288-0

Laumann, D., Schlummer, P., Abazi, A., Borkamp, R., Lauströer, J., Pernice, W., Schuck, C., Schulz-Schaeffer, R., & Heusler, S. (2024). Analyzing the effective use of augmented reality glasses in University Physics Laboratory Courses for the example topic of optical polarization. *Journal of Science Education and Technology*, *33*(5), 668–685. https://doi.org/10.1007/s10956-024-10112-0

Leny, L., Wahidah, M., & Muhammad, K. (2024). Development of e-modules of basic laws of chemistry based on problem-based learning to improve critical thinking skills. *Jurnal Inovasi Teknologi Pendidikan*, *11*(4), 367–376. https://doi.org/10.21831/jitp.v11i4.72576

Lichtenberger, A., Hofer, S. I., Stern, E., & Vaterlaus, A. (2025). Enhanced conceptual understanding through formative assessment: Results of a randomized controlled intervention study in physics classes. *Educational Assessment, Evaluation and Accountability*, *37*(1), 5–33. https://doi.org/10.1007/s11092-024-09445-6

López-Bouzas, N., del Moral-Pérez, M. E., & Castañeda-Fernández, J. (2024). Improved socio-emotional skills in students with autism spectrum disorder (ASD) following an intervention supported by an augmented gamified environment. *International Journal of Child-Computer Interaction*, *42*, 1-12. https://doi.org/10.1016/j.ijcci.2024.100683

Mahendru, N., Mai, N., & Hin, H. S. (2024). Elevating Students' shared learning experiences with augmented reality in a digital marketing classroom. *International Journal of Learning, Teaching and Educational Research*, *23*(5), 87–106. https://doi.org/10.26803/ijlter.23.5.5

Mokmin, N. A. M., Su, H., Chen, J., & Qi, S. (2023). Impact of an AR-based learning approach on the learning achievement, motivation, and cognitive load of students on a design course. *Journal of Computers in Education*, *11*(2), 557–574. https://doi.org/10.1007/s40692-023-00270-2

Mukhlisin, M., Gani, H. A., & Purnamawati, P. (2022). The overview of needs analysis for development learning model based on digital in vocational education. *Proceedings of the 1st World Conference on Social and Humanities Research (W-SHARE 2021)*, *654*, 105–108. https://doi.org/10.2991/assehr.k.220402.023

Mukhlisin, M., Gani, H. A., Purnamawati, P., & Muhammad, U. (2022). Rancang bangun media pembelajaran mikrokontroller berbasis augmented reality (AR). *Joule (Journal of Electrical Engineering)*, *3*(1), 125–129. https://doi.org/10.61141/joule.v3i1.240

Mukhlisin, M., Ponta, T., & Syafar, M. (2023). Aplikasi pembelajaran mata kuliah embedded system berbasis mobile augmented reality (Mar). *INSTEK: Jurnal Informatika Sains dan Teknologi*, *8*(1), 46–55. https://doi.org/10.24252/instek.v8i1.36704

Naithani, U., & Guleria, V. (2024). Integrative computational approaches for discovery and evaluation of lead compound for drug design. *Frontiers in Drug Discovery*, *4*, 1-11. https://doi.org/10.3389/fddsv.2024.1362456

Namkoong, K., Leach, J., Chen, J., Zhang, J., & Weichelt, B. (2023). A feasibility study of augmented reality intervention for safety education for farm parents and children. *Frontiers in Public Health*, *10*, 1-11. https://doi.org/10.3389/fpubh.2022.903933

Palada, B., Chandan, V. S., Gowda, C. P. A., & Nikitha, P. (2024). The role of augmented reality (AR) in education. *International Journal for Research in Applied Science and Engineering Technology*, *12*(3), 1400–1408. https://doi.org/10.22214/ijraset.2024.59079

Quang, N. Van, & Duc, N. M. (2023). Developing problem-solving and creativity skills in high school students through chemistry teaching in Vietnam: Current status and solution. *International Journal of Multidisciplinary Research and Growth Evaluation*, *4*(6), 897–903. https://doi.org/10.54660/.ijmrge.2023.4.6.897-903

Singh, G., & Ahmad, F. (2024). An interactive augmented reality framework to enhance the user experience and operational skills in electronics laboratories. *Smart Learning Environments*, *11*(1), 1–23. https://doi.org/10.1186/s40561-023-00287-1

Tatić, D., & Tešić, B. (2017). The application of augmented reality technologies for the improvement of occupational safety in an industrial environment. *Computers in Industry*, *85*, 1–10. https://doi.org/10.1016/j.compind.2016.11.004

Thohir, M. A., Sukarelawan, M. I., Jumadi, J., Warsono, W., & Citrasukmawati, A. (2021). The effects of instructional design based web course on pre-service teachers' competencies. *International Journal of Evaluation and Research in Education (IJERE)*, *10*(1), 230-236. https://doi.org/10.11591/ijere.v10i1.20475

Tiwari, A. S., Bhagat, K. K., & Lampropoulos, G. (2024). Designing and evaluating an augmented reality system for an engineering drawing course. *Smart Learning Environments*, *11*(1), 1–19. https://doi.org/10.1186/s40561-023-00289-z

Turkcan, H., Imamoglu, S. Z., & Ince, H. (2023). Impact of augmented reality on operational performance: The mediating role of process innovativeness. *Journal of Manufacturing Technology Management*, *34*(8), 1313–1331. https://doi.org/10.1108/JMTM-05-2023-0171

Zhao, G., Sheng, H., Wang, Y., Cai, X., & Long, T. (2025). Generative artificial intelligence amplifies the role of critical thinking skills and reduces reliance on prior knowledge while promoting in-depth learning. *Education Sciences*, *15*(5), 1-19. https://doi.org/10.3390/educsci15050554

Zou, Y. L., Kuek, F., Feng, W. Z., & Cheng, X. (2025). Digital learning in the 21st century: trends, challenges, and innovations in technology integration. *Frontiers in Education*, *10*, 1-11. https://doi.org/10.3389/feduc.2025.1562391