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# Analysis of the Use of Augmented Reality-Based Learning Media on Conceptual Understanding Ability

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**Abstract:** In the era of technological advancement, education must continually innovate by utilizing effective learning media, such as augmented reality (AR). AR creates an interactive and engaging learning environment by combining real-world visualization with virtual objects, making it a focus in education to enhance conceptual understanding. This study aims to analyze the validity, practicality, and effectiveness of AR-based learning media in improving students' conceptual understanding of computer hardware materials in Informatics subjects. The research was conducted in classes X TKJ 1 and X TKJ 2 at SMK Negeri 5 Padang, using multiple-choice objective test instruments and questionnaires. The results indicate that the use of AR-based learning media has a significant impact on improving students' conceptual understanding. This is evidenced by the hypothesis test results showing a sig. (2-tailed) value of 0.00 (<0.05) and an N-gain score of 0.7293 (high category), with an effectiveness percentage of 72.92%. AR-based learning media was deemed highly feasible as supplementary learning media based on expert validation (95%), as well as practicality questionnaires from teachers (95%) and students (87%). The advantages of AR media include realistic visualization, the ability for repeated observation, a more interactive learning experience, and efficiency in the use of teaching aids. Thus, the implementation of AR in learning has proven effective in enhancing students' conceptual understanding and providing a more engaging and meaningful learning experience.

**Keywords**: Augmented reality; Learning media; Computer hardware; Informatics; Conceptual understanding.

## 1. Introduction

Education plays a pivotal role in the development of a nation by producing competent human resources who are prepared to face global challenges [1]–[3]. In the era of rapid advancements in information and communication technology, the educational sector must continuously innovate, particularly in adopting effective learning media that align with technological trends [1], [4], [5]. Among these innovations, augmented reality (AR)-based interactive learning media has gained significant attention due to its potential to create engaging and immersive learning environments [6]. AR integrates virtual objects with real-world contexts in real-time, enhancing conceptual understanding by offering learners an enriched and interactive visualization experience [7]–[9].

Recent studies have demonstrated that AR-based applications are highly feasible and effective for classroom implementation. When integrated into vocational education settings, particularly for the introduction of electronic components and hardware systems, AR-based learning tools have proven to be beneficial in improving students' engagement and comprehension [10], [11]. These findings support the growing consensus that interactive learning tools, especially those utilizing AR, are vital in complementing traditional learning resources such as textbooks and student worksheets.

A notable example of such innovation is the AR-based learning media developed in accordance with the Kurikulum Merdeka. This media allows students to independently or collaboratively learn hardware-related concepts through 3D marker-based scanning via smartphones. Developed specifically for the Informatics subject in Indonesian vocational high schools, the media provides modular content tailored to the curriculum and aims to enhance both accessibility and interactivity in the learning process.

The development of this AR-based media is motivated by the practical challenges faced during the teaching of computer hardware components at SMK Negeri 5 Padang. The subject matter, which falls under the Computer System element of Informatics, is ideally supported by physical laboratories and real-life demonstrations. However, the limited availability of computer laboratories—only four for the entire school—poses significant constraints. These facilities are primarily allocated for students in majors such as Computer and Network Engineering, Civil Engineering, and Industrial Electronics, leaving students in other departments with insufficient access to essential tools and infrastructure.

Data from the 2024 academic year indicate a total of 454 tenth-grade students across 15 departments, highlighting the inadequacy of existing facilities. Many classes are forced to relocate to the library for theoretical sessions due to scheduling conflicts and laboratory shortages. Additionally, the school has only five projectors, limiting multimedia-assisted instruction. Budget limitations restrict the procurement of lab equipment and instructional tools, further impeding the delivery of practical lessons—particularly those requiring direct observation of computer hardware.

Another significant barrier is the limited availability of comprehensive learning resources. Students often struggle to understand the functions and structures of computer hardware solely through textbooks. Teacher-centered instruction remains dominant, and while multimedia tools such as projectors are occasionally used, they are insufficient in promoting interactive and experiential learning. Interviews with Informatics teachers reveal that students exhibit low engagement and retention when not exposed to practical demonstrations or immersive media. Moreover, there is a tendency among students to perceive learning merely as answering questions rather than attaining meaningful conceptual understanding.

This concern is particularly relevant in teaching Generation Z students, who are digital natives with distinct learning preferences. For them, technology is not a luxury but a necessity. Therefore, educators must align their instructional strategies with the students' digital proclivities by incorporating technology not merely as a support tool, but as an integral part of content delivery—both in and outside the classroom [12]–[14].

Against this backdrop, this research focuses on the development and validation of AR-based interactive learning media for teaching computer hardware in vocational high schools. The objectives are to (1) design AR-integrated instructional tools based on the national curriculum, (2) evaluate the media's validity and practicality, and (3) assess its effectiveness in enhancing students' conceptual understanding. The study is expected to offer a scalable model for the integration of AR in vocational education and contribute to bridging the gap between theoretical knowledge and practical application in technology-rich environments.

## 2. Material and methods

### 2.1 Research Design and Setting

This study used a quantitative approach with a quasi-experimental design to analyze the effectiveness of augmented reality (AR)-based learning media in enhancing students' conceptual understanding. The research was conducted at SMK Negeri 5 Padang, located on Jl. Beringin Raya No. 4, Lolong Belanti, Padang Utara, West Sumatra, during the odd semester of the 2024/2025 academic year in July 2024.

### 2.2 Population and Sample

The population in this study consisted of all tenth-grade students at SMK Negeri 5 Padang, totaling 454 students across 15 vocational majors. The sample was determined purposively, focusing on the TKJ (Computer and Network Engineering) department based on teacher recommendations. This group was selected due to better attendance and class scheduling suitability.

**Table 1.** Population and Sample

| Population | Sample |
|---|---|
| All 10th-grade students (n=454) | 10th-grade students in TKJ |

## 2.3 Variables and Operational Definitions

The independent variable (X) was the AR-based interactive learning media developed for the topic "Computer Hardware" in the Informatics subject. The dependent variable (Y) was students' conceptual understanding, measured through a structured cognitive test aligned with conceptual indicators such as restating concepts, classifying, providing examples, and applying concepts to problem-solving.

## 2.4 Research Instruments

The conceptual understanding test comprised 25 multiple-choice items and was administered as a pre-test and post-test. The instrument was validated through a pilot study involving 31 students from Grade XI TKJ.

**Table 2.** Conceptual Understanding Indicators and Items

| Indicator | Item Numbers |
|---|---|
| Restating a concept | 1, 2, 3 |
| Classifying objects by characteristics | 4, 5, 6, 7 |
| Giving examples and non-examples | 8, 9, 10 |
| Presenting the concept in various representations | 11, 12, 13, 14 |
| Developing necessary or sufficient conditions | 15, 16, 17, 18 |
| Using appropriate procedures or operations | 19, 20, 21 |
| Applying concepts to solve problems | 22, 23, 24, 25 |

### 2.4.1 Validity

The validity of the test items was analyzed using Pearson Product-Moment correlation [15]. The formula used is:

$$r_{xy} = \frac{N.\sum XY - (\sum X)(\sum Y)}{\sqrt{[N(\sum X^2) - (\sum X)^2][N(\sum Y^2) - (\sum Y)^2]}} \quad (1)$$

Description:
rxy = Correlation index value "r"
N = Number of cases (sample size)
∑XY = Sum of the products of scores X and Y
∑X = Total score of X
∑Y = Total score of Y

After that, the rxy result is compared with the r product moment at a 5% significance level. If rxy > rtable with α = 5%, the item is considered valid; in other words, if rxy < rtable, the item is considered invalid. For objective-type questions, the item score is 1 if answered correctly and 0 if answered incorrectly. A question item is considered valid if the Sig. value is < 0.05.

**Table 3.** Validity Test Results

| Number of Items | Valid Items | Percentage |
|---|---|---|
| 25 | 15 | 60% |

Based on the validity test results shown in Table 3, out of 25 multiple-choice items tested, 15 items were found to be valid, which represents 60% of the total. This indicates that more than half of the items meet the validity criteria, where the rxy value is greater than the rtable at a significance level of 5% (α = 0.05) or the Sig. value is less than 0.05. Each item was scored as 1 for a correct answer and 0 for an incorrect one. The validity test ensures that the questions accurately measure students' understanding of the material, and the results confirm that a majority of the items are suitable for use in the assessment instrument.

### 2.4.2 Reliability

Reliability was analyzed using Cronbach's Alpha [16], with the following formula:

$$r_{11} - \left(\frac{k}{(k-1)}\right)\left(1 - \frac{\sum \sigma_b^2}{\sigma_t^2}\right) \tag{2}$$

Description:
r11 = the reliability being measured
$\sum \sigma_b^2$ = the sum of the variances of each item score
$\sigma_b^2$ = total variance
k = number of question items

The results of the test instrument reliability analysis can be seen in the following table:

**Table 4.** Test Instrument Reliability Results

| Statistic | Test Items |
|---|---|
| r11 | 0.721 |
| **Conclusion** | **High Reliability** |

Table 4 presents the results of the reliability test for the test instrument. The reliability coefficient (r11) obtained is 0.721. According to reliability classification standards, a coefficient value between 0.70 and 0.90 indicates high reliability. This means the test items demonstrate consistent and stable results, making the instrument suitable for measuring students' conceptual understanding. The high reliability score also suggests that the items have minimal measurement error and can be used confidently in the evaluation process.

### 2.4.3 Difficulty Level

Difficulty level was measured using:

$$P = \frac{B}{JS} \tag{3}$$

Description:
P = difficulty level
B = the number of students who answered correctly
JS = the total number of students.

**Table 5.** Item Difficulty Level

| Category | Number of Items | Percentage |
|---|---|---|
| Easy | 16 | 64% |
| Moderate | 9 | 36% |
| Difficult | 0 | 0% |

The table presents the distribution of test items based on their difficulty level. Out of a total of 25 items, 16 items (64%) fall into the "Easy" category, indicating that the majority of questions were easily answered by students. Meanwhile, 9 items (36%) are categorized as "Moderate," showing a balanced level of challenge for learners. Notably, there are no items classified as "Difficult" (0%), which implies that all questions were within an accessible range of difficulty. This distribution suggests that the test is generally easy to moderate, which can be appropriate for measuring basic conceptual understanding, but may need to be adjusted in future assessments to include a few more challenging items for better differentiation among students' abilities.

### 2.4.4 Discriminatory Power

Discriminatory power was calculated as:

$$D = \frac{BA}{JA} - \frac{BB}{JB} = PA - PB \tag{4}$$

Description:

D = Discrimination index of each item
BA = Number of correct responses from the upper group

BB = Number of correct responses from the lower group
JA = Maximum possible score for the upper group
JB = Maximum possible score for the lower group
PA = Proportion of upper group participants who answered correctly
PB = Proportion of lower group participants who answered correctly

**Table 6.** Discriminatory Power

| Category | Number of Items | Percentage |
|---|---|---|
| Poor | 6 | 24% |
| Fair | 9 | 36% |
| Good | 10 | 40% |
| Excellent | 0 | 0% |

The table shows the classification of test items based on their discrimination index, which indicates how well each item can distinguish between high-performing and low-performing students. Out of 25 items, 6 items (24%) are categorized as "Poor," meaning these items have low ability to differentiate between students with different levels of understanding. Nine items (36%) fall into the "Fair" category, indicating moderate discriminative power. The majority, 10 items (40%), are in the "Good" category, suggesting they are effective in identifying differences in students' performance. Notably, there are no items in the "Excellent" category (0%), which implies that none of the items reached the highest standard of discrimination. Overall, while most items perform adequately or well, there is still room for improvement, especially in enhancing item quality to increase their ability to discriminate more effectively.

### 2.5 Validation and Practicality Instruments

Validation and practicality questionnaires were used to assess the feasibility and usability of the AR-based media. The validation instrument was completed by three expert reviewers, while practicality instruments were completed by two teachers and participating students.

**Table 7.** Validation Questionnaire Blueprint

| No | Indicator |
|---|---|
| 1 | Content relevance |
| 2 | Visual design and layout |
| 3 | Usability |
| 4 | Interactivity and communication |

**Table 8.** Practicality Questionnaire Blueprint (Teachers)

| No | Indicator |
|---|---|
| 1 | Content relevance |

| No | Indicator |
|---|---|
| 2 | Visual design and layout |
| 3 | Usability |
| 4 | Interactivity and communication |

**Table 9.** Practicality Questionnaire Blueprint (Students)

| No | Indicator |
|---|---|
| 1 | Ease of use |
| 2 | Time efficiency |
| 3 | Content alignment |
| 4 | Attractiveness |
| 5 | Independent usability |

All items in both questionnaires were rated using a 4-point Likert scale and validated by educational experts.

## 2.6 Data Collection Procedure

The research was conducted in three phases: administering the pre-test, implementing the AR-based learning session, and administering the post-test. After the intervention, practicality questionnaires were distributed to students and teachers, and validation forms were submitted to expert reviewers.

## 2.7 Data Analysis

Preliminary analyses involved testing data for normality and homogeneity to ensure the assumptions of parametric testing were met. Following this, a paired t-test was performed to determine whether there was a statistically significant difference between pre-test and post-test results. To further assess the effectiveness of the intervention, the Normalized Gain (N-gain) was calculated using the formula:

$$N - gain = \frac{(\text{Posttest} - \text{Pretest})}{\text{Maximum Score} - \text{Pretest})} \quad (5)$$

This calculation provided insights into learning improvement and the effectiveness of the AR media in enhancing conceptual understanding. Additionally, descriptive analysis was applied to evaluate questionnaire data from both expert validators and research participants.

## 3. Results and discussion

### 3.1 Pretest Results

The pretest results obtained from classes X TKJ 1 and X TKJ 2 in this study are presented in the following figure.

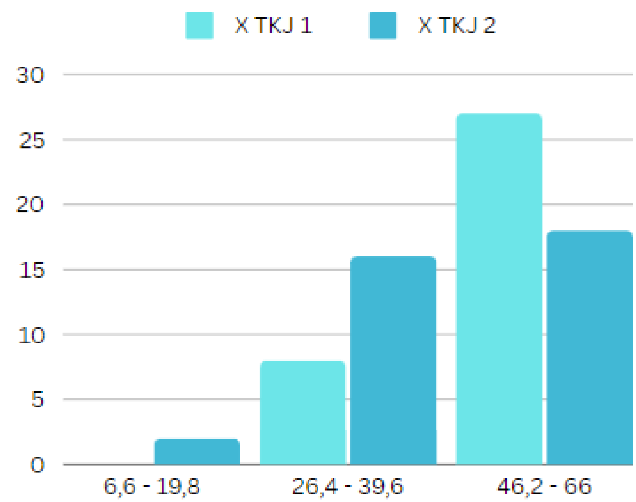


**Figure 1.** Frequency Diagram of Pretest Results

Based on the diagram above, no students from class X TKJ 1 scored within the lowest range (6.6 – 19.8). However, 8 students (22.86%) scored within the low range (26.4 – 39.6). Meanwhile, in class X TKJ 2, 2 students (5.56%) scored in the lowest range, and 16 students (45.71%) scored in the low range. Furthermore, 27 students (77.14%) in class X TKJ 1 achieved scores in the highest range (46.2 – 66), while in class X TKJ 2, 18 students (51.43%) scored in the highest range.

Based on statistical calculations, measures of central tendency and data dispersion from the pretest scores are shown in Table 10 below:

**Table 10.** Measures of Central Tendency and Dispersion of Pretest Results

| No | Measures of Central Tendency and Dispersion | Pre-test Scores | |
|---|---|---|---|
| | | X TKJ 1 | X TKJ 2 |
| 1 | Lowest Score | 33.00 | 13.20 |
| 2 | Highest Score | 66.00 | 66.00 |
| 3 | Mean | 52.04 | 42.53 |
| 4 | Median | 52.80 | 42.90 |
| 5 | Mode | 52.80 | 26.40 |
| 6 | Standard Deviation | 10.34 | 14.15 |

Based on the table above, it can be seen that the lowest score obtained in class X TKJ 1 was 33.00, while in class X TKJ 2 it was 13.20. The highest score in both classes was 66.00. Furthermore, the average score in class X TKJ 1 was 52.046, whereas in class X TKJ 2 it was 42.53. The median or middle value in class X TKJ 1 was 52.80, while in class X TKJ 2 it was 42.90. The mode, or most frequently occurring score, in class X TKJ 1 was 52.8, whereas in class X TKJ 2 it was 25.4. The standard deviation in class X TKJ 1 was 10.34, while in class X TKJ 2 it was 14.15.

### 3.2 Posttest Results

The posttest results obtained from class X TKJ 1 and X TKJ 2 in this study are presented in the following figure.

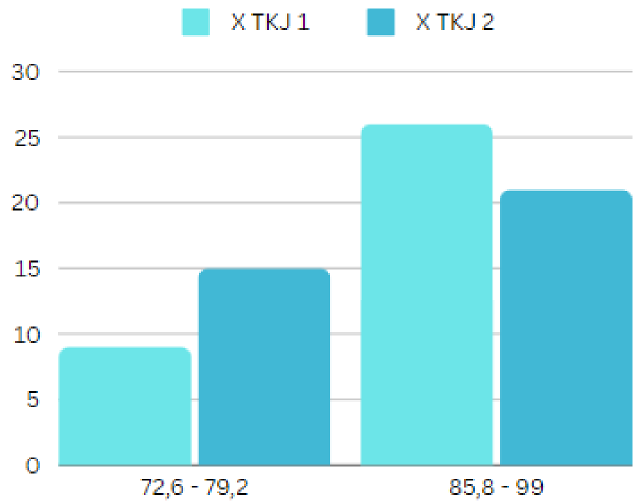


**Figure 2.** Frequency Diagram of Posttest Results

Based on the diagram above, 9 students (25.71%) in class X TKJ 1 scored within the range of 72.6–79.2, while in class X TKJ 2, 15 students (42.86%) scored within the same range. Additionally, 26 students (74.29%) in class X TKJ 1 scored within the highest range (85.8–99), while 21 students (60%) in class X TKJ 2 scored in that range.

Based on statistical calculations, the measures of central tendency and data dispersion for the posttest scores are shown in Table 11 below:

**Table 11.** Measures of Central Tendency and Dispersion of Posttest Results

| No | Measures of Central Tendency and Dispersion | Post-test Scores | |
|---|---|---|---|
| | | X TKJ 1 | X TKJ 2 |
| 1 | Lowest Score | 72.60 | 72.60 |
| 2 | Highest Score | 99.00 | 92.40 |
| 3 | Mean | 87.12 | 84.15 |
| 4 | Median | 85.80 | 85.80 |
| 5 | Mode | 85.80 | 85.80 |

| No | Measures of Central Tendency and Dispersion | Post-test Scores | |
|---|---|---|---|
| | | X TKJ 1 | X TKJ 2 |
| 6 | Standard Deviation | 71.22 | 55.50 |

Based on the table above, it can be seen that the lowest posttest score obtained by both classes was 72.6. The highest score achieved in class X TKJ 1 was 99.0, while in class X TKJ 2 it was 92.4. Furthermore, the average score in class X TKJ 1 was 87.120, whereas in class X TKJ 2 it was 84.150. The median or middle score for both classes was 85.80. The most frequently occurring score, or mode, in both classes was also 85.8. The standard deviation in class X TKJ 1 was 71.228, while in class X TKJ 2 it was 55.501.

### 3.3 Recapitulation of Pretest and Posttest Data

At the beginning of the study in classes X TKJ 1 and X TKJ 2, teaching was conducted using conventional methods, followed by a pretest to assess students' initial conceptual understanding of the material. Based on the table above, the average (mean) score for class X TKJ 1 during the pretest was 52.046, while class X TKJ 2 had an average score of 42.533. This indicates that both classes had relatively similar levels of initial conceptual understanding before the treatment was given.

In subsequent sessions, both classes received treatment in the form of learning using augmented reality-based media, followed by a posttest to measure students' conceptual understanding after the treatment. Based on the posttest results, an improvement was observed in both classes. This improvement is evident in the increase in the average (mean) scores of both classes. The mean score for class X TKJ 1 increased by 35.074, while the mean score for class X TKJ 2 increased by 41.617.

### 3.4 Normality Test

The normality test was conducted using SPSS 25.0 software with the criterion that data is considered normally distributed if the significance value is greater than α = 0.05. If the significance value is less than α = 0.05, the data is considered not normally distributed. The results of the normality test are shown in Table 12 below:

**Table 12.** Normality Test Results

**Tests of Normality**

| | Kolmogorov-Smirnov[a] | | |
|---|---|---|---|
| | Statistic | df | Sig. |
| Posttest X TKJ 1 | .126 | 35 | .174 |
| Posttest X TKJ 2 | .142 | 35 | .070 |

a. Lilliefors Significance Correction

Based on the testing criteria, if the significance value is greater than α = 0.05, the data is normally distributed. The significance value of the posttest data for class X TKJ 1 is 0.174 > α = 0.05, indicating that the final data is normally distributed. The significance value for class X TKJ 2 is 0.070 > α = 0.05, which also means the final data is normally distributed.

### 3.5 Homogeneity Test

This process was conducted using SPSS 25 software. The assessment criterion is that if the test result shows a p-value > α = 5% or a probability greater than 0.05, the data is considered homogeneous. The results of the homogeneity test for the pretest data are shown in Table 13 below:

**Table 13.** Pretest Data Homogeneity Test Results

**Test of Homogeneity of Variance**

| | | Levene Statistic | df1 | df2 | Sig. |
|---|---|---|---|---|---|
| PRETEST | Based on Mean | 2.675 | 1 | 68 | .107 |

It can be seen that the significance value is 0.107. This indicates that the obtained significance value is greater than 0.05 or sig = 0.107 > 0.05, meaning the pretest data is homogeneous. Thus, it can be concluded that the pretest data for class X TKJ 1 and X TKJ 2 are equivalent. The results of the homogeneity test for the posttest data are shown in Table 14 below:

**Table 14.** Posttest Data Homogeneity Test Results

**Test of Homogeneity of Variance**

| | | Levene Statistic | df1 | df2 | Sig. |
|---|---|---|---|---|---|
| POSTTEST | Based on Mean | 1.594 | 1 | 68 | .211 |

It can be seen that the significance value is 0.211. This shows that the significance value obtained is greater than 0.05 or sig = 0.211 > 0.05, which means the posttest data is homogeneous. Therefore, it can be concluded that the posttest data for class X TKJ 1 and X TKJ 2 are equivalent.

### 3.6 Paired Sample t-Test

Next, a hypothesis test was conducted using the paired sample t-test. The purpose of the paired sample t-test is to evaluate the effect of treatment on the same sample at two different times — before and after using augmented reality-based learning media [17]. The decision rule for accepting or rejecting Ho in this test is: if the significance value > 0.05, then Ho is accepted (Ha is rejected); if the significance value < 0.05, then Ho is rejected (Ha is accepted).

The paired sample t-test was performed using SPSS 25.0 software. The test results are shown in Table 15 below:

**Table 15.** Paired Sample t-Test Results

**Paired Samples Test**

| | | Paired Differences | | | | | t | df | Sig. (2-tailed) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | 95% Confidence Interval of the Difference | | | | |
| | | Mean | Std. Deviation | Std. Error Mean | Lower | Upper | | | |
| Pair 1 | Pretest X TKJ - Posttest X TKJ | -38.3743 | 14.3588 | 1.7162 | -41.7980 | -34.9506 | -22.360 | 69 | .000 |

Based on the results of the paired sample t-test, the sig. (2-tailed) value is 0.00 < 0.05. Based on this result, it can be concluded that the alternative hypothesis ($H_a$) is accepted, indicating that the use of augmented reality-based learning media has an influence on students' conceptual understanding ability. This is also supported by the difference in the average student scores before and after the treatment.

## 3.7 Normalized Gain Test

The results of the previously conducted normality test showed that the pretest and posttest scores for both class X TKJ 1 and X TKJ 2 were normally distributed. The homogeneity test indicated that the pretest and posttest scores of both classes had homogeneous variances. This was followed by hypothesis testing using the paired sample t-test to determine whether the use of augmented reality-based learning media had a significant effect before and after its implementation.

After conducting the paired sample t-test, the effectiveness of augmented reality-based learning media in improving conceptual understanding was evaluated using the normalized gain (N-Gain) test. The results of the normalized gain test are shown in Table 16 below:

**Table 16.** Normalized Gain Test Results

**Descriptive Statistics**

| | N | Minimum | Maximum | Mean | Std. Deviation |
|---|---|---|---|---|---|
| NGain_Score | 70 | .33 | 1.00 | .7293 | .14864 |
| NGain_Persentase | 70 | 33.33 | 100.00 | 72.9252 | 14.86427 |
| Valid N (listwise) | 70 | | | | |

Based on the table above, the N-Gain score is 0.7293, which falls into the high category, and the N-Gain percentage is 72.92%, indicating that the use of augmented reality-based learning media for improving conceptual understanding is categorized as “effective” [18].

### 3.8 Validity Test

The validity test of the augmented reality-based learning media was conducted by three independent media experts with relevant academic and professional backgrounds. The assessment focused on key indicators such as content relevance and alignment, design and appearance, usability, and interactivity. The total score obtained from the expert evaluations was 68.33 out of a maximum possible score of 72. The percentage score was calculated using the following formula:

$$P = \frac{\sum R}{N} X\ 100\% = \frac{68,33}{72} X\ 100\% = 95\% \tag{5}$$

This percentage indicates that the developed learning media is categorized as Highly Feasible for educational implementation.

### 3.9 Practicality Test

The practicality of the media was evaluated by a subject-matter teacher of Informatics and by students from class X TKJ at a vocational high school. The teacher's assessment covered various indicators such as usability, time efficiency, attractiveness, clarity of interpretation, alignment with the subject matter, and practical applicability in teaching. The total average score given was 49.33 out of 52, resulting in the following calculation:

$$P = \frac{49.33}{52} X\ 100\% = 95\% \tag{7}$$

This result places the media in the Highly Practical category according to the teacher's perspective.

Additionally, the students evaluated the media based on similar indicators, including ease of use, efficiency, engagement, content relevance, and overall usability for learning. The average score given by students was 38.22 out of 44, and the practicality percentage was calculated as:

$$P = \frac{38.22}{44} X\ 100\% = 87\% \tag{8}$$

This indicates that from the students' perspective, the learning media is also considered Highly Practical and suitable for use in the classroom environment.

### 3.10 Discussion

The hypothesis testing using the paired sample t-test for class X TKJ 1 and X TKJ 2 yielded a significance value of 0.00 (2-tailed), which is less than the significance threshold of α = 0.05. This result confirms that the implementation of augmented reality (AR)-based learning media has a statistically significant impact on students' conceptual understanding in the subject of Informatics. Specifically, the mean score of class X TKJ 1 increased from 52.046 (pretest) to 87.120 (posttest), while class X TKJ 2 improved from 42.533 to 84.150. This suggests that students experienced substantial learning gains after the introduction of AR media in the learning process.

The use of conventional teaching methods, which predominantly rely on lectures and textbook-based explanations, often results in reduced student engagement, especially when dealing with abstract or highly visual subjects such as computer hardware. Traditional learning resources generally present only static 2D images, limiting the ability of learners to fully comprehend the structure, form, and function of each hardware component [19]–[21]. In contrast, AR allows for the presentation of interactive 3D models within real-world environments, enabling students to explore learning materials in a more engaging, realistic, and immersive manner [22]–[25].

The developed AR-based learning media in this study integrates not only visual 3D content but also a modular structure accompanied by quizzes. These features have been shown to support both knowledge retention and cognitive development by promoting active learning and enabling students to self-assess their understanding [26], [27]. The practicality test results from students yielded a score of 87%, while the teacher evaluation reached 95%, classifying the media as highly practical in both cases. Moreover, the expert validation score of 95% indicated that the media was highly feasible for classroom implementation.

These findings are consistent with prior research which emphasizes that AR-enhanced instruction can increase learning motivation, improve academic performance, and foster higher-order thinking skills [28], [29]. AR media provide multiple pedagogical benefits, including the ability to visualize complex concepts realistically, perform repeated observations, support experiential learning without physical lab equipment, and optimize instructional efficiency [30].

However, some technical limitations were encountered during implementation. For instance, the AR marker-based system occasionally exhibited instability when users moved their hands, causing the virtual objects to disappear from the screen. Additionally, performance issues such as lagging and application crashes were noted on devices with limited hardware capabilities. These challenges have been highlighted in other studies, which emphasize the importance of adequate device specifications and user interface design in ensuring effective AR integration in learning environments [31]–[33].

Despite these constraints, the results of this study demonstrate that AR-based learning media meet the criteria of validity, practicality, and effectiveness. The findings support the assertion that AR represents a promising technology in educational innovation, particularly in vocational education settings where visual interaction with learning materials is critical [10].

## 4. Conclusion

This study confirms that the use of augmented reality (AR)-based learning media significantly enhances students' conceptual understanding in the subject of Informatics. Statistical analysis using the paired sample t-test revealed a significant effect, further supported by an N-gain score of 0.7293 and an effectiveness percentage of 72.92%, both indicating a high level of instructional impact. The AR-based media was also rated as highly feasible by expert validators (95%) and perceived as highly practical by both teachers and students.

The primary strengths of the developed AR media include realistic 3D visualization, opportunities for repeated observation, interactive and immersive learning experiences, and efficient use of instructional resources. These features are well aligned with the demands of vocational education, particularly in domains where spatial reasoning and visual comprehension are essential.

Nonetheless, several technical constraints were identified during implementation, such as instability of AR visual objects when markers were not held steadily and application lag on devices with lower hardware specifications. While these limitations did not compromise the overall effectiveness of the intervention, they highlight areas for technical improvement and adaptation in future implementations.

Given the promising results and identified limitations, further research is recommended to examine the long-term impact of AR-based media on learning retention, engagement, and transferability across different subjects and educational levels. In particular, future studies could explore how AR can be integrated with other emerging technologies, such as gamification or artificial intelligence, to further enhance its pedagogical potential. Broader trials in diverse classroom settings are also needed to validate scalability and adaptability across various learning contexts.

## Author's declaration

### Author contribution

**Delfi Ardius Gulo**: Was responsible for the conceptualization and design of the study, development of the CT-based Programming E-Module, data collection, and drafting of the manuscript. **Denny Kurniadi**: Contributed to the validation process, feasibility analysis, refinement of instructional content, and critical review of the manuscript. Both authors have read and approved the final version of the article.

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### Competing interest

The authors declare no competing interest.

### Ethical clearance

This research did not involve human or animal subjects.

### AI statement

This article is the author's original work, written from original research and no sections or figures are generated by AI. English is checked using Grammarly and has been verified by the authors.

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