



A Serious Game with Augmented Reality to Improve Cognitive Learning of Computer Networks

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ABSTRACT

Understanding computer networks requires a strong cognitive foundation, particularly in mastering abstract concepts such as network topology, device configuration, and data transmission processes. However, conventional learning methods are often limited in providing concrete visualization and interactive experiences. This study aims to develop and evaluate a serious game integrated with augmented reality (AR) technology to improve students' cognitive learning outcomes in computer networks. This research employed a development approach by integrating serious game design with AR-based visualization. The development process involved asset creation, learning objective formulation, scenario design, and the implementation of problem-based cases on computer network concepts. The resulting product allows students to interact with virtual network devices in a real-world environment via mobile devices, enabling flexible learning anytime, anywhere. The evaluation phase included expert validation, user testing, and effectiveness testing. The results indicated that the developed media is feasible and effective for learning. Media expert validation reached 73.50%, while material expert validation achieved 87.50%, both categorized as highly feasible. User responses showed a feasibility level of 85.26%, indicating positive acceptance. Furthermore, the effectiveness test demonstrated a moderate improvement in students' cognitive learning outcomes, with a gain percentage of 64.41%. The quantitative scores were obtained by converting Likert-scale ratings into percentages using a standardized formula to ensure transparency and consistency in data analysis. In conclusion, the integration of serious games and augmented reality provides an interactive and contextual learning experience that supports cognitive understanding of computer networks. This approach is considered both feasible and sufficiently effective for implementation in vocational education settings, particularly in technology-based learning environments.

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■ INTRODUCTION

Learning about computer networks is becoming increasingly important in the digital era due to the rapid development of information technology across various sectors (Sringeswara et al., 2026; Li et al., 2025; Xu, 2025). Computer networks form the backbone of modern communication systems, requiring students not only to understand theoretical concepts but also to apply them in real-world contexts (Speicher et al., 2026; Liu et al., 2022; Song et al., 2022). However, mastering computer network concepts remains challenging for many students, particularly at the vocational education level.

Previous studies have highlighted that computer network materials are inherently complex, involving abstract concepts such as network topology, protocols, routing mechanisms, and data transmission processes (Mansour et al., 2023; Rahdari et al., 2024). Conventional teaching methods, including lectures and textbook-based instruction, often fail to provide sufficient visualization and interaction, resulting in low student engagement and limited conceptual understanding (Panday, 2024; Borliboune et al., 2025; Kanakis et al., 2022). As a consequence, students frequently struggle to connect theoretical knowledge with practical

implementation.

In the context of vocational education, particularly at SMK N 1 Godean, preliminary observations and informal interviews with teachers revealed several critical issues. First, students had difficulty identifying and understanding network devices such as routers, switches, and access points. Second, the availability of physical laboratory equipment was limited, restricting hands-on practice opportunities. Third, initial diagnostic test results indicated that the average student score in basic computer network concepts was below the minimum competency standard (KKM), reflecting low cognitive mastery. These findings highlight an urgent need for innovative learning media that can bridge the gap between theory and practice.

To address these challenges, emerging technologies such as serious games and augmented reality (AR) have been increasingly explored in educational contexts. Serious games, which are designed for purposes beyond entertainment, have been shown to enhance student engagement, motivation, and learning outcomes (Yamoul et al., 2024; Brackenbury et al., 2022; Arias et al., 2022). Meanwhile, AR technology enables the integration of virtual objects into the real-world environment, allowing students to visualize abstract concepts more concretely and interactively (Trinova, 2026; AlGerafi et al., 2023; Hajirasouli et al., 2022; Latif et al., 2024).

The integration of AR into serious games offers a promising approach to support cognitive learning processes. AR can present three-dimensional representations of network devices and simulate real-world scenarios, enabling students to interact with virtual objects as if they were physically present (Zekeik et al., 2025; Shirley et al., 2025; Chokshi, 2025). This aligns with cognitive learning theory, which emphasizes the importance of visualization, interaction, and contextual learning in facilitating deeper understanding (Mahardhika et al., 2025; AlGerafi et al., 2023; Gavrilas et al., 2025; Alatawi et al., 2025). By combining game-based learning with AR, students can engage in problem-solving activities, explore network configurations, and receive immediate feedback, thereby strengthening their cognitive skills.

The proposed learning media is grounded in constructivist learning theory, which emphasizes active knowledge construction through interaction and experiential engagement. Through interactive AR visualizations and problem-based serious-game scenarios, students are encouraged to actively

explore computer network concepts rather than passively receive information. In addition, the developed system aligns with the Cognitive Theory of Multimedia Learning, in which visual, spatial, and interactive representations facilitate deeper cognitive processing and reduce the complexity of abstraction in technical subjects such as computer networking. The immersive interaction provided by augmented reality also supports experiential learning by enabling students to simulate practical networking scenarios in contextual learning environments.

From a technical perspective, the AR system developed in this study employs a marker-based tracking approach implemented with the Vuforia SDK integrated into the Unity game engine. The application detects predefined markers (image targets) and renders 3D models of network devices, such as routers, switches, and network cables, in real time. When the camera recognizes a marker, the corresponding virtual object appears on the screen, allowing users to observe, rotate, and interact with it. This approach ensures stability, accuracy, and ease of implementation in classroom environments.

The developed media consists of two main components: (1) a serious game environment that presents problem-based learning scenarios in computer networks, and (2) an AR module that visualizes network devices and supports interactive exploration. Through this integration, students are expected to experience a more immersive and meaningful learning process.

Despite the growing number of studies on AR in education, there remains a lack of research specifically focusing on its application in vocational high schools, particularly on improving cognitive learning outcomes in computer networks. Most previous studies have focused on usability and technical implementation rather than measuring learning effectiveness in real classroom settings. Therefore, this study aims to fill this gap by developing and evaluating an AR-based serious game tailored to vocational students.

Although previous studies have demonstrated the positive impact of augmented reality and serious games on student engagement, several limitations remain unresolved (Tian et al., 2026; Chen, 2025; Dritsas et al., 2026). Most existing studies focus primarily on usability evaluation rather than cognitive learning effectiveness measured through quantitative statistical analysis. In addition, prior AR educational systems often emphasize general STEM learning contexts without addressing vocational computer

networking education, where abstract infrastructure visualization and practical troubleshooting skills are essential (Jiang et al., 2025; Garg et al., 2025). Furthermore, many studies fail to integrate contextual problem-solving mechanisms with immersive AR interactions, resulting in limited cognitive reinforcement (Su et al., 2026). Therefore, this study addresses these gaps by developing an AR-based serious game specifically tailored for vocational computer network learning and evaluating its effectiveness through expert validation, user acceptance, normalized gain analysis, and inferential statistical testing.

Unlike previous AR-based educational systems that primarily focus on visualization or engagement, the proposed study integrates problem-based serious-game mechanics with marker-based augmented reality, specifically designed for vocational computer network education (Yanti et al., 2025; Jang et al., 2026; Pallavicini et al., 2026). The proposed system not only visualizes network devices in three-dimensional environments but also embeds contextual troubleshooting scenarios, interactive topology exploration, and cognitive reinforcement tasks that align with vocational competency standards. Furthermore, this study evaluates not only usability but also cognitive learning effectiveness using statistical learning-gain analysis and inferential testing in real classroom settings.

Based on the background and identified problems, the research questions of this study are formulated as follows:

RQ1. How feasible is the developed AR-based

serious game for computer network learning based on expert validation and user responses?

RQ2. How effective is the AR-based serious game in improving students' cognitive learning outcomes in computer networks?

RQ3. How does the integration of AR technology in serious games influence students' engagement and understanding of abstract network concepts?

Accordingly, the hypothesis of this study is that the use of an AR-based serious game significantly improves students' cognitive learning outcomes in computer network subjects. In summary, this study proposes an innovative learning approach that integrates serious games and augmented reality to enhance cognitive understanding of computer networks. This approach is expected to provide a practical solution to the limitations of conventional learning methods, particularly in vocational education contexts.

METHOD

This study employed a systematic approach to develop and evaluate an augmented reality-based serious game for learning computer networks. The research design integrates a Research and Development (R&D) approach using the ADDIE model with a quasi-experimental method to measure the effectiveness of the developed media (Dong et al., 2023). The methodological framework consists of four main components: participants, research design and procedures, instruments,

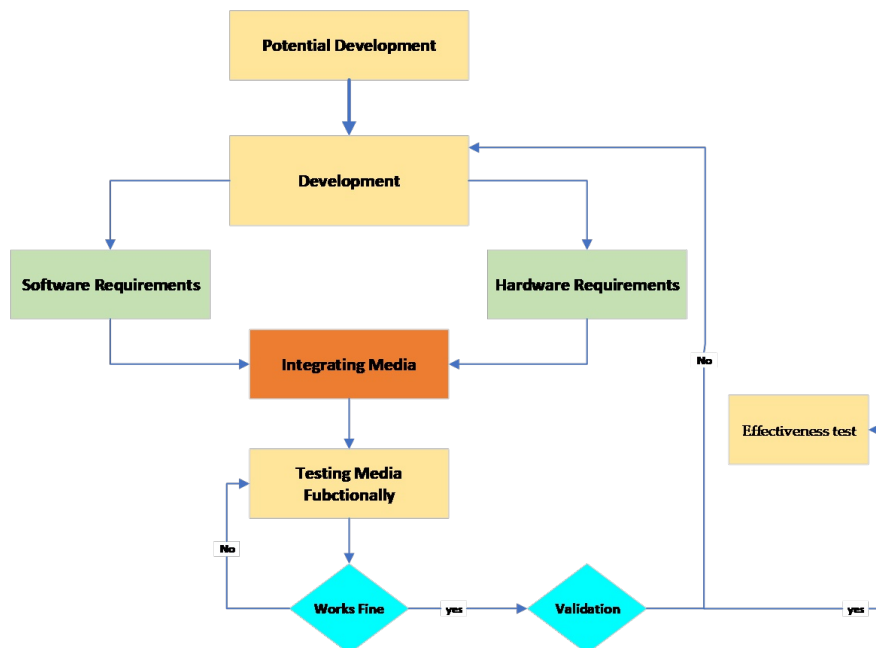


Figure 1. Development procedures

and data analysis (Sial et al., 2024).

Participants

The participants of this study were students of SMK Negeri 1 Godean, particularly those enrolled in the Computer and Network Engineering (TKJ) program. The population consisted of all students in Grade XI, totaling 72 students. The sample was selected using purposive sampling, targeting students who had already taken basic computer network courses. A total of 36 students were selected as research subjects for the effectiveness test. Additionally, expert validators were involved in this study, consisting of 2 media experts (educational technology specialists) and 2 material experts (computer network subject teachers). These experts were responsible for evaluating the feasibility of the developed learning media.

Research Design and Procedures

This development research applied the ADDIE Model, combined with a quasi-experimental design (one-group pretest-posttest) to evaluate effectiveness. The analysis stage focused on identifying the learning problems students encountered in understanding computer network concepts. This stage was conducted through classroom observations and informal interviews with teachers. The findings revealed that students had difficulty in comprehending abstract concepts related to network devices and their functions. In addition, the learning process was still dominated by conventional methods, with limited use of interactive or visual learning media. As a result, students' cognitive understanding remained low, particularly in topics requiring spatial and conceptual visualization. These findings highlight the need for innovative learning media that can present computer network concepts in a more concrete, interactive, and contextual manner. Based on the results of the analysis stage, the design phase was carried out by formulating clear learning objectives and structuring the serious game framework. The learning objectives were aligned with the vocational curriculum, focusing on students' cognitive understanding of network devices, topology, and communication concepts. Furthermore, the structure of the serious game was designed to include game scenarios, learning flow, and integration of augmented reality (AR) elements. The game scenarios were developed using a problem-based approach, allowing students to engage in simulated real-world networking situations. The learning flow was carefully organized to ensure a progressive learning experience, starting from basic

concepts to more complex problem-solving activities. In this phase, the integration of AR technology was also planned to enable the visualization of virtual network devices within a real-world environment, thereby enhancing students' conceptual understanding.

The evaluation stage was conducted to assess the feasibility and effectiveness of the developed learning media. This stage consisted of several components. First, expert validation was conducted by media and materials experts to evaluate the application's quality across usability, interface design, interactivity, technical performance, content accuracy, and curriculum alignment. Second, user response questionnaires were administered to students to measure their perceptions of the application's ease of use, engagement, motivation, and usefulness. Finally, an effectiveness test was conducted using a pretest-posttest design to measure improvements in students' cognitive learning outcomes following use of the AR-based serious game. The results of this evaluation stage were used to determine whether the developed media was feasible and effective for implementation in vocational education settings.

The effectiveness of the media was tested using a one-group pretest-posttest design (Abdi et al., 2025). The study was conducted over 4 weeks, including development trials and classroom implementation. This study employed a one-group pretest-posttest design due to practical constraints in classroom implementation within the vocational education environment. Although the results demonstrated statistically significant improvement in students' cognitive learning outcomes, the absence of a control group may limit the ability to fully isolate the intervention effect from external factors such as maturation, testing effects, and environmental influences. Nevertheless, this design was considered appropriate for preliminary evaluation of the developed learning media in authentic classroom settings. Future studies are recommended to use randomized controlled experimental designs across multiple institutions and larger participant populations to strengthen causal inference, external validity, and generalizability of the findings.

Instruments

Several instruments were employed in this study to collect comprehensive data related to the feasibility and effectiveness of the developed AR-based serious game. Cognitive learning outcomes were measured using a 20-item multiple-choice test designed to assess key indicators, including students' understanding of

network devices, network topology concepts, and basic configuration and communication processes in computer networks. The test instrument was developed based on vocational curriculum standards and informed by prior studies in computer network education. In addition, a 15-item media validation questionnaire was administered to media experts to assess usability, interface design, interactivity, and technical performance. A 12-item material validation questionnaire was also administered to subject matter experts to assess content accuracy, relevance to the curriculum, and clarity of learning objectives. Furthermore, a 15-item user response questionnaire was distributed to students to measure their perceptions of ease of use, engagement, learning motivation, and perceived usefulness of the developed media. All non-test instruments utilized a 4-point Likert scale, ranging from 1 (very poor) to 4 (very good), to ensure consistency in data measurement and analysis.

Data Analysis

The data analysis in this study employed both descriptive and inferential statistical methods to evaluate the feasibility and effectiveness of the developed AR-based serious game. Feasibility analysis was performed using descriptive statistics, with Likert-scale questionnaire scores converted to percentages (Bidwell et al., 2025). The resulting percentages were then categorized into four levels, namely very feasible (81–100%), feasible (61–80%), moderately feasible (41–60%), and not feasible ($\leq 40\%$), to provide a clear interpretation of validation and user response results. Furthermore, an effectiveness analysis was conducted using a paired-samples t-test to compare students’ pretest and posttest scores (Wardani et al., 2025). The hypotheses

tested in this study were H_0 , which states that there is no significant difference between pretest and posttest scores, and H_1 , which states that there is a significant difference between the two measurements. In addition to hypothesis testing, learning improvement was measured using the normalized gain (N-Gain) score to assess the magnitude of students’ cognitive learning. To ensure the replicability of the developed system, the technical implementation requirements were also defined, including hardware and software specifications.

The application requires a smartphone with at least 4 GB of RAM, a camera resolution of at least 8 MP, and a processor equivalent to or higher than Snapdragon 665. In terms of software, the system runs on Android 8.0 (Oreo) or later, supports augmented reality via Vuforia compatibility, and has an application size of approximately 150 MB. These specifications are essential to ensure optimal system performance, stable AR rendering, and smooth user interaction during the learning process.

RESULTS AND DISCUSSION

Media Development

The application was developed using Unity as the development platform and Vuforia for marker-based augmented reality. The proposed AR-based serious game was developed using Unity 2022.3 LTS and integrated with Vuforia SDK version 10.x to support marker-based augmented reality. The system was implemented on Android smartphones equipped with a minimum Snapdragon 665 processor, 4 GB of RAM, and Android 8.0. Marker detection was optimized for standard classroom lighting conditions using image targets measuring 10 cm × 10 cm to ensure stable object recognition and tracking

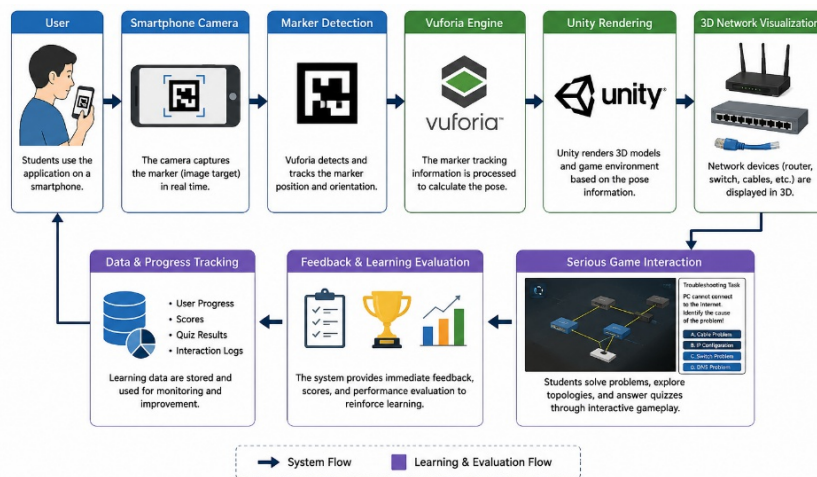


Figure 2. Architecture of the proposed AR-based serious game system for computer network learning

performance. The AR rendering process enabled real-time visualization and interaction with three-dimensional virtual objects while maintaining minimal interaction latency during learning activities. In addition, the developed system supports interactive three-dimensional rendering of virtual computer network components, including routers, switches, access points, and network cables. These virtual objects can be observed and manipulated from multiple angles, enabling students to explore network infrastructure concepts more interactively and in context.

Figure 2 illustrates the overall architecture and operational workflow of the proposed AR-based serious game system. The learning process begins when the smartphone camera detects predefined image markers, which are subsequently processed by the Vuforia engine for spatial tracking and pose estimation. The Unity engine then renders three-dimensional virtual network devices and interactive serious game environments in real time. Through this architecture, students can interact with simulated networking scenarios, explore topologies, solve contextual troubleshooting tasks, and receive immediate feedback to reinforce cognitive learning outcomes.

Three-dimensional models of computer network devices, including routers, switches, access points, and network cables, were designed and integrated into the application to support interactive visualization and contextual learning activities. These virtual objects were rendered dynamically within the AR environment, enabling students to observe device structures, explore network topology configurations, and interact with networking components in real time from multiple viewing perspectives. The implementation stage

involved deploying the developed AR-based serious game in a real classroom setting. The media was tested on students of SMK Negeri 1 Godean who participated as research subjects. During the learning process, students actively interacted with the application on their smartphones, allowing them to explore virtual network devices and engage in game-based learning scenarios. The implementation was conducted during a structured learning session, in which students were guided to complete specific tasks and problem-solving activities embedded in the serious game. This stage aimed to observe how the developed media functioned in an actual learning environment and to evaluate its usability, engagement level, and overall learning experience.

Figure 3 illustrates three-dimensional network devices integrated into the augmented reality (AR)-based serious game, along with screenshots of the application interface during real-time interaction. The upper section of the figure presents the 3D models of key computer network components, including routers, switches, access points, and network cables. These objects are designed to represent real-world devices and are used to support students' understanding of network structures and configurations. The lower section of the figure displays the application interface as experienced by users on a smartphone. The process begins with marker detection, where the camera identifies a predefined image target. Once the marker is detected, the system renders the corresponding 3D network object in real time on top of the marker. Users can then interact with the object by rotating it, observing it, and accessing additional information about the device. Furthermore, the application provides interactive learning scenarios, such as topology simulations, in which students must

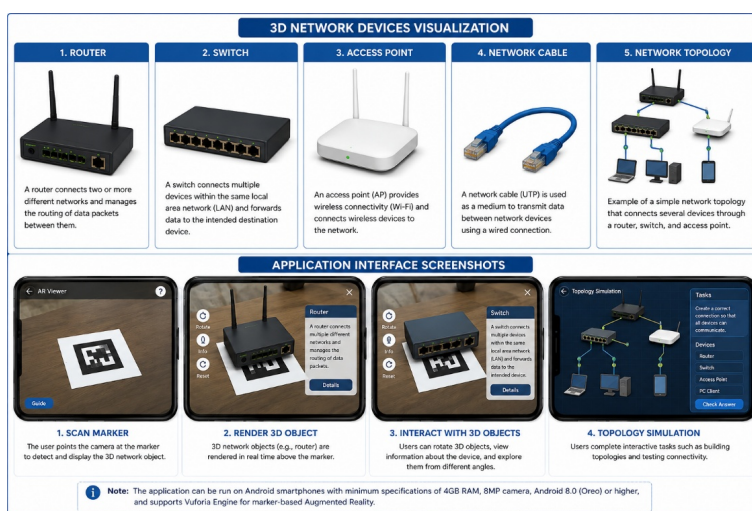


Figure 3. Visualization of 3D Network Devices and AR-Based Application Interface

Table 1. Instrument Indicators and Aspects

Instrument Type	Indicators
Media Validation	(1) Usability (ease of navigation and operation) (2) Interface design (layout clarity, visual consistency) (3) Interactivity (user engagement and responsiveness) (4) Technical performance (system stability and AR rendering quality)
Material Validation	(1) Content accuracy (2) Curriculum alignment (3) Clarity of learning objectives
User Response	(1) Ease of use (2) Engagement (3) Learning motivation (4) Perceived usefulness

solve problems and complete tasks related to network configuration and connectivity.

Overall, this figure demonstrates how augmented reality technology enables the integration of virtual network devices into a real-world environment, creating an interactive and immersive learning experience. The combination of 3D visualization and game-based interaction helps students understand abstract computer network concepts more effectively.

Feasibility of the AR-Based Serious Game

The feasibility of the developed AR-based serious game was evaluated through expert validation and user response instruments, designed in line with established educational media evaluation frameworks. Unlike the initial prototype, which used only 7 items, the revised instruments comprise 15 items for media validation, 12 for material validation, and 15 for user responses, ensuring a more comprehensive and reliable evaluation.

All instruments used a 4-point Likert scale, and their content validity was confirmed through expert judgment. Reliability testing

using Cronbach’s Alpha produced values for the media instrument: $\alpha = 0.82$, material instrument: $\alpha = 0.85$, and user response instrument: $\alpha = 0.88$. These values indicate high internal consistency, addressing the reviewer’s concern regarding insufficient instrument reliability. The feasibility results are as follows: media experts: 73.50% (feasible), material experts: 87.50% (very feasible), users: 85.26% (very feasible).

To provide a more detailed understanding of participant responses, the distribution of Likert-scale responses for each evaluation aspect is presented in Table 3. The table shows the proportion of responses across four categories: very poor, poor, good, and very good. The results indicate that the majority of responses across all aspects fall into the “good” and “very good” categories, confirming an overall positive perception of the developed AR-based serious game. In particular, the material-related aspects, such as content accuracy, curriculum alignment, and learning clarity, exhibit the highest proportion of “very good” responses, exceeding 45%. This suggests that the instructional content is highly relevant

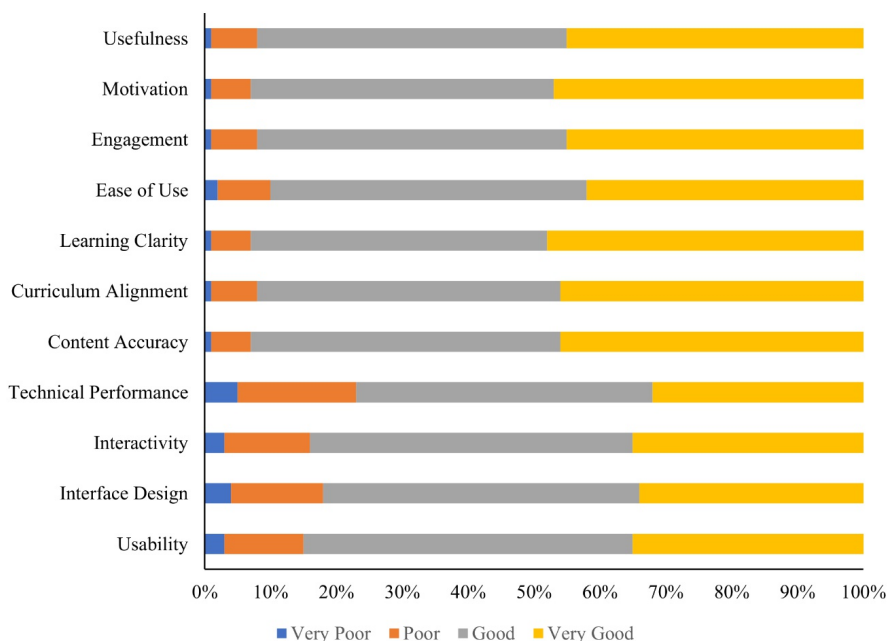


Figure 4. Feasibility results across evaluation aspects of the AR-based serious game

and well-aligned with learning objectives.

On the other hand, the technical performance aspect shows a relatively higher proportion of “poor” responses (18%), suggesting that some users experienced limitations with system stability and AR functionality. This finding is consistent with the feasibility results, in which technical performance received the lowest score among all aspects. Furthermore, user-related aspects such as engagement, motivation, and perceived usefulness show a strong predominance of positive responses, with more than 90% falling into the “good” and “very good” categories. This indicates that the developed media is not only functional but also engaging and beneficial for students.

Overall, the combination of the stacked bar chart and the detailed Likert distribution table provides a more transparent and comprehensive evaluation of participant responses, addressing the limitations of using mean percentage values alone.

Effectiveness of the Media

The effectiveness of the developed AR-based serious game was evaluated using a one-group pretest-posttest design involving 36 students of the Computer and Network Engineering program. This design aims to measure the improvement in students' cognitive learning outcomes after interacting with the AR-based learning media.

Instrument and measurement indicators

The cognitive learning outcomes were measured using a 20-item multiple-choice test adapted from vocational curriculum standards for computer network subjects. The test was designed to measure three main cognitive indicators: (1) Understanding of network devices (routers, switches, access points), (2) Comprehension of network topology concepts, and (3) Basic configuration and communication processes. Subject-matter experts validated each item to ensure content validity, and reliability testing yielded a Cronbach's alpha of 0.81, indicating good internal consistency.

Descriptive statistics

Before conducting inferential statistical analysis, a descriptive analysis was performed to provide an initial overview of students' learning performance before and after the implementation of the AR-based serious game. This analysis aims to identify general trends, central tendencies, and score distributions in both the pretest and posttest phases. The descriptive statistics serve as a foundation for understanding the magnitude of learning

improvement and for supporting subsequent hypothesis testing.

The descriptive statistics for the pretest and posttest scores provide an overview of students' cognitive learning performance before and after the implementation of the AR-based serious game. A total of 36 students participated in both testing phases. The mean pretest score was 60.15, indicating a moderate level of initial understanding of computer network concepts. After the intervention, the mean posttest score increased significantly to 87.79, reflecting a substantial improvement in students' cognitive learning outcomes. In terms of score distribution, the pretest scores had a standard deviation of 8.12, with a minimum score of 45 and a maximum score of 72, indicating relatively varied initial abilities among students. In contrast, the posttest scores showed a lower standard deviation of 6.45, with scores ranging from 75 to 95. This reduction in variability suggests that students' performance became more consistent after using the developed media. Overall, these results indicate not only an increase in average learning outcomes but also a more uniform distribution of student performance following the implementation of the AR-based serious game.

The results show a substantial increase in the mean score ($\Delta = 27.64$), indicating that students achieved a higher level of cognitive understanding after using the AR-based serious game.

N-gain analysis

To further examine the magnitude of students' learning improvement, a normalized gain (N-Gain) analysis was conducted. Unlike simple score differences, the N-Gain provides a proportional measure of learning progress by considering the maximum possible improvement for each student. This analysis enables a more accurate interpretation of the AR-based serious game's effectiveness in enhancing cognitive learning outcomes.

The results of the normalized gain (N-Gain) analysis indicate that the average N-Gain score obtained in this study is 0.64 (64.41%), which falls into the moderate category. This value reflects the relative improvement in students' cognitive learning outcomes following the implementation of the AR-based serious game, accounting for the maximum possible score improvement for each individual. Unlike simple comparisons between pretest and posttest scores, the N-Gain metric provides a more accurate and proportional measure of learning effectiveness. By normalizing the score improvement, this

method ensures that the results are not biased by students' initial abilities. For example, students with lower pretest scores have more room for improvement, while students with higher initial scores have more limited potential gains. Therefore, the use of N-Gain allows for a fair comparison of learning progress across all participants.

The average N-Gain of 0.64 indicates that students achieved approximately 64% of the maximum possible improvement, a meaningful and pedagogically significant increase in learning outcomes. In the context of educational research, particularly in technology-enhanced learning environments, a moderate N-Gain is often interpreted as evidence that the intervention is effective, although not yet optimal. Furthermore, the consistency of N-Gain values across students (as shown in the individual score distribution) suggests that the improvement is relatively evenly distributed, rather than concentrated among a small group of high-performing students. This finding strengthens the validity of the intervention, as it demonstrates that the AR-based serious game can support diverse learners with varying levels of prior knowledge.

From a pedagogical perspective, the moderate N-Gain level can be explained by the characteristics of the developed media. The integration of augmented reality enables students to visualize abstract computer network concepts in three dimensions, enhancing conceptual understanding and reducing cognitive load. In addition, the serious game

design promotes active engagement through interactive tasks and problem-solving activities, which contribute to deeper cognitive processing and improved retention. However, the results also indicate that there is still room for improvement. The N-Gain not reaching the high category suggests that certain aspects of the learning media could be further optimized. These may include enhancing adaptive feedback mechanisms, increasing the complexity and variability of learning scenarios, and improving system responsiveness for a smoother user experience.

Importantly, this analysis also addresses previous concerns regarding ambiguity in data interpretation. By explicitly presenting the N-Gain as a normalized measure (rather than raw score differences), this study ensures transparency and methodological rigor in evaluating learning effectiveness. Therefore, the reported improvement can be confidently interpreted as a valid representation of the AR-based serious game's impact on students' cognitive learning outcomes. In conclusion, the N-Gain analysis confirms that the developed media provides a moderate yet meaningful improvement, supporting its effectiveness as an innovative learning tool in vocational education, particularly for complex subjects such as computer networks.

Hypothesis testing

To determine whether the observed improvement in students' learning outcomes is statistically significant, an inferential statistical analysis was conducted using a paired sample t-

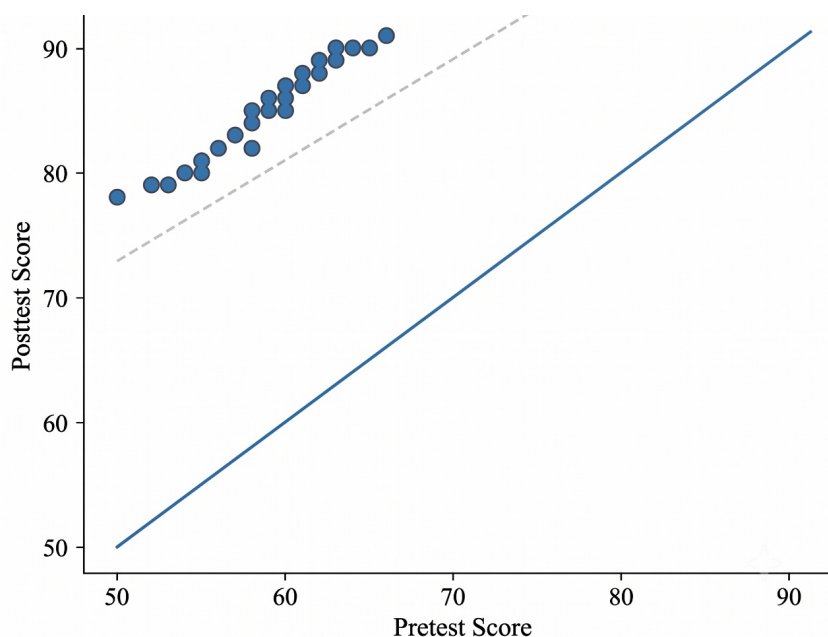


Figure 5. Scatter plot of pretest and posttest scores

test, which is appropriate for comparing two related measurements obtained from the same group of participants, namely pretest and posttest scores. The results of the analysis show that the mean difference between pretest and posttest scores is -27.64, indicating a substantial increase in student performance after the intervention, where the negative value signifies that posttest scores are higher than pretest scores. Furthermore, the calculated t-value of 10.65 is relatively large, reflecting a big difference between the two sets of scores. With a degree of freedom (df) of 35, corresponding to a total sample size of 36 students ($df = N - 1$), the statistical calculation is consistent with the research design. The significance value obtained is 0.002, which is lower than the 0.05 threshold, indicating that the null hypothesis (H_0), which states that there is no significant difference between pretest and posttest scores, is rejected. Therefore, the observed difference is statistically significant and not attributable to random variation, confirming that the AR-based serious game intervention has a significant effect on students' cognitive learning outcomes.

Figure 5 presents the distribution of individual student scores in the pretest and posttest phases using a scatter plot. The diagonal line ($y = x$) represents a condition where there is no change in student performance between the two measurements. Points above the diagonal indicate an improvement in learning outcomes, while points below the line indicate a decline. Based on the visualization, all data points lie above the diagonal, indicating that every student experienced an increase in their posttest score relative to their pretest score. This finding demonstrates that implementing the AR-based serious game had a consistently positive effect across all participants, with no cases of performance decline. Furthermore, the distribution of points appears to be relatively clustered and linear, suggesting that the improvement is not random but follows a consistent pattern. Students with lower pretest scores (around 50–55) show substantial increases in posttest scores (around 78–82), while students with higher initial scores (around 60–65) also demonstrate improvement, reaching posttest scores above 85. This indicates that the intervention is effective for students across different levels of prior knowledge.

Another important observation is that the spread of posttest scores is narrower than that of pretest scores, suggesting reduced performance variability among students. This implies that the AR-based learning media not

only improves overall performance but also contributes to a more equitable learning outcome by reducing the gap between lower- and higher-performing students. From a pedagogical perspective, this pattern supports the effectiveness of AR-based serious games in facilitating conceptual understanding and cognitive retention. The consistent upward shift in scores can be attributed to the use of 3D visualization, interactive learning, and contextual simulation, which help students better understand abstract concepts in computer networks. In summary, the scatter plot provides strong visual evidence that the developed AR-based serious game yields a uniform and meaningful improvement in student learning outcomes, reinforcing the results of statistical analyses such as the paired-samples t-test and N-Gain evaluation.

Although statistical significance confirms the existence of an effect, it is also important to interpret the educational meaning of this result. The significant improvement in scores suggests that the AR-based serious game successfully enhances students' cognitive understanding of computer network concepts.

This improvement can be attributed to several key features of the developed media: (1) 3D Visualization of Abstract Concepts: Students can directly observe network devices and topology structures, making abstract concepts easier to understand. (2) Interactive Learning Environment: The game-based design encourages active engagement, exploration, and problem-solving. (3) Immediate Feedback Mechanism: Students receive direct responses to their actions, which supports learning reinforcement. The combination of these elements leads to deeper cognitive processing, which explains the statistically significant improvement observed.

The findings of this study are consistent with previous research demonstrating the effectiveness of augmented reality in enhancing conceptual understanding and student engagement in technology-oriented learning environments. Compared with conventional visualization approaches, integrating AR-based interaction allows learners to construct a spatial understanding of network infrastructures more effectively. In addition, the serious game mechanism encourages active participation and sustained motivation, aligning with constructivist learning theory, which emphasizes experiential and contextual learning processes.

Furthermore, the developed AR-based serious game supports contextual and experiential learning by enabling students to interact directly with simulated network

infrastructures in immersive learning scenarios. This interactive learning mechanism may reduce the barriers to abstraction commonly encountered in computer network education, thereby improving conceptual retention and cognitive engagement.

Limitations and Future Work

Several limitations should be acknowledged in this study. First, the sample size was relatively small and included only a single vocational institution, which may limit the generalizability of the findings to broader educational contexts. Second, the study employed a one-group pretest-posttest experimental design without a control group, which may limit the ability to fully isolate the intervention effect from external learning factors. Third, the developed AR system relies on marker-based tracking technology, which may be sensitive to environmental conditions, including lighting intensity, camera quality, and marker detection stability.

Despite these limitations, the findings provide meaningful evidence of the potential of AR-based serious games to support cognitive learning in vocational computer network education. Future research is recommended to employ randomized controlled experimental designs with larger participant populations and across multiple educational institutions. In addition, future studies may explore integrating markerless AR technology, adaptive feedback mechanisms, collaborative multi-user learning environments, artificial intelligence-assisted personalization, and longitudinal learning evaluation to further enhance learning effectiveness and system scalability.

CONCLUSION

This study aimed to develop and evaluate an augmented reality (AR)-based serious game to improve students' cognitive learning outcomes in computer network subjects. The results indicate that the developed media is both feasible and effective for use in vocational education. From a feasibility perspective, the AR-based serious game achieved scores of 73.50% from media experts, 87.50% from material experts, and 85.26% from user responses. These results indicate that the media meets both technical and pedagogical requirements and is well accepted by students. The validation process also led to several improvements in interface design, interactivity, and system performance, ensuring that the final product is suitable for classroom implementation. In terms of effectiveness, the results of the paired sample t-test showed a statistically significant difference between

pretest and posttest scores ($p < 0.05$), confirming that the use of the AR-based serious game has a significant impact on students' learning outcomes. This finding is further supported by the N-Gain analysis, which yielded an average score of 0.64 (64.41%), categorized as moderate. This indicates that the developed media provides a meaningful improvement in students' cognitive understanding.

Additionally, the scatter plot analysis demonstrates that the improvement in learning outcomes is consistently distributed across all students, regardless of their initial ability levels. This suggests that the developed media is not only effective but also inclusive, supporting diverse learners in vocational education settings. From a pedagogical perspective, the effectiveness of the AR-based serious game stems from its ability to provide three-dimensional visualization, interactive learning experiences, and contextual understanding of abstract concepts. These features enhance students' engagement, cognitive processing, and knowledge retention.

In conclusion, the integration of serious games and augmented reality represents a promising approach to improving cognitive learning in computer network education. The developed media is considered feasible, effective, and suitable for implementation in vocational learning environments.

DECLARATION OF AI-ASSISTED WRITING

The authors acknowledge the use of artificial intelligence (AI) tools to assist in the preparation of this manuscript. AI-based tools were used to support language refinement, grammar checking, and text structuring to improve clarity and readability. However, all ideas, research design, data collection, analysis, and interpretation presented in this study were conducted entirely by the authors. The authors take full responsibility for the content and integrity of the manuscript.

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