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Development of Interactive Multimedia and Evaluation of Basic Electronics Learning Outcomes among Vocational High School Students

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Abstract

This study developed web-based interactive multimedia to teach basic electronics, focusing on simple digital circuits in the Fundamentals of Computer Network and Telecommunications Engineering subject. Development followed the Define, Design, Develop, and Disseminate stages. Evaluation included eight functional test scenarios, ratings from five validators, observations during two learning sessions, and a nonequivalent control-group pretest-posttest assessment involving 36 Grade 10 students, with 18 students in each group. All reported functional test scenarios passed, and validator ratings averaged 86% of the maximum score. All six implementation indicators were recorded as completed in both sessions. Mean scores increased from 61.78 to 83.33 in the experimental group and from 57.33 to 73.00 in the control group. Within-group improvements were statistically significant, but the between-group difference in mean improvement was not; Welch's $t(31.77) = 1.969$, $p = .058$. Multimedia use was accompanied by improved scores on the assessed digital circuit content, positive validator ratings, and successful completion of the reported functional tests. However, the study did not establish greater learning improvement than conventional instruction.

Keywords: Basic electronics; Learning outcomes; Interactive learning multimedia; Web-based learning; Vocational education.

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Introduction

Basic Electronics provides a foundation for understanding electronic systems relevant to vocational competencies in Computer and Network Engineering (TKJ). This study focuses specifically on Simple Digital Circuits taught within the Fundamentals of Computer Network and Telecommunications Engineering subject. The learning content addresses logic-gate operations and the relationships among gate symbols, logical expressions, truth tables, and circuit input–output conditions. Understanding these relationships requires more than memorizing gate functions; students need opportunities to manipulate inputs, predict outputs, and explain circuit behavior. Interactive multimedia can support these activities by presenting connected representations and allowing repeated exploration. Accordingly, this study evaluates learning outcomes related to the specified digital circuit content rather than basic electronics as a whole.

The learning environment at Bina Insan Mandiri Integrated Vocational School (SMKS Terpadu Bina Insan Mandiri) served as a basis for developing the multimedia in this study. Based on the reported needs identification, students still struggle to understand abstract electronics concepts, while limited lab equipment reduces opportunities for direct circuit exploration. These problems relate to the material's characteristics, which require observing relationships among symbols, components, and circuit behavior. For example, understanding logic gates goes beyond stating AND, OR, or NOT functions; it also includes predicting outputs as input conditions change. Students can do these activities with physical equipment, but they require enough components, time, and a lab setup. Therefore, supporting media are needed that let students observe changes in circuit conditions and check results repeatedly without relying entirely on laboratory equipment.

Digital simulations are one alternative for meeting these needs. Through simulations, students can manipulate specific variables, observe system responses, and compare the observed results with previously learned concepts. (Li & Liang, 2024) analyzed 46 studies from 22 publications on virtual laboratories in engineering education. The meta-analysis yielded an overall effect size of 0.686 for Hedges' g, indicating a trend towards positive results across various indicators of engineering education. However, the researchers emphasized that virtual laboratories cannot fully replace hands-on experience with physical devices. This finding offers important considerations for learning Basic Electronics. Simulations can help students understand circuit principles before or during practical activities, while hands-on experience remains necessary to develop skills in handling components and taking measurements. Thus, interactive multimedia is better positioned as a learning support tool rather than a replacement for all practical activities.

In vocational education, learning technology use should reflect the relationship between targeted competencies and the learning experiences provided. (Frady, 2023) reviewed the use of virtual laboratories in engineering technology

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education and vocational training, highlighting their relevance to competency-oriented learning. This study showed that implementing virtual laboratories must align with vocational education's pedagogical design and characteristics. For Basic Electronics, this means providing activities that are not only visually appealing but also help students understand technical principles and procedures. Therefore, multimedia development should begin with a needs analysis, set learning objectives, and select interaction methods appropriate to the material's characteristics.

Web-based interactive multimedia learning brings materials, visuals, simulations, exercises, and feedback into a single learning environment. In the logic gates section, students can study circuit symbols, change input conditions, observe outputs, and compare them to truth tables. This relationship is important because digital logic concepts involve distinct but interrelated representations. Gate symbols represent logic operations, truth tables describe possible input-output relationships, and circuit visualizations show how these operations are implemented. If these three concepts are presented separately without a clear relationship, students must make their own connections. In contrast, an integrated presentation provides opportunities to examine these relationships through interactive activities. However, its pedagogical value still needs to be demonstrated through learning evaluations, not simply inferred based on the completeness of the application's features.

The study by (Wibawanto et al., 2022) provides an example of developing multimedia simulations in vocational education. The study developed media for practical land surveying learning by including assessments from experts, teachers, and students, and by measuring learning outcomes. The results showed positive assessments of the developed multimedia and higher learning outcomes for the experimental group than for the comparison group. These findings suggest that simulations can be integrated into vocational learning and evaluated through product quality indicators and learning outcomes. However, learning in land surveying differs from Basic Electronics. Field measurement simulations focus on procedures and spatial representation, while electronics simulations emphasize the relationships among components, electrical conditions, and circuit responses. These differences explain the need to develop and evaluate simulations that specifically account for the characteristics of electronic materials.

A study by (Yang et al., 2024) also showed that simulation technology can support practical skills learning in science and engineering education. Through a meta-analysis of virtual reality use, the study found a positive effect size for students' practical skills. However, immersive virtual reality technology differs from web-based interactive multimedia in devices, user experience, and forms of interaction. Therefore, this study's results cannot be used as direct evidence that web-based multimedia will have the same effect. Its relevance lies in providing learning experiences that let students interact with representations of objects or processes. In Basic Electronics, this principle applies through circuit simulations and changes in input-output conditions directly related to learning objectives.

Interactive media design also requires attention to the quality of the resulting learning experience. Technology with many features may not support student understanding if navigation is complex, instructions are unclear, or visual representations do not align with learning objectives. A systematic review of virtual reality features for skills training (Tusher et al., 2024) discussed how technology characteristics relate to the learning process. The study showed the need to consider how technology features support learning activities and how their outcomes are evaluated. Although the study focuses on different contexts, these considerations remain relevant for web-based interactive multimedia. Ease of navigation, material suitability, visual quality, and instruction clarity represent distinct aspects of multimedia use and therefore require separate consideration. Assessing these aspects can help identify areas that need improvement before wider use.

Beyond student interfaces, multimedia development can also include features that help teachers manage learning activities. Web-based applications can integrate features such as material management, assignments, evaluation, and monitoring student progress. (Elmoazen et al., 2023; Englis & Frederiks, 2024; Lawson et al., 2024) examined learning analytics in virtual laboratories and identified several approaches to using student activity data to understand the learning process. The study showed that digital environments can provide information about user interactions, but using it requires an appropriate evaluation design. In the context of Basic Electronics multimedia, learning outcome monitoring features can help teachers access assessment information available in the application. However, these features do not automatically demonstrate improved teaching quality. The benefits must be distinguished between the success of the technical functions and their impact on learning implementation.

Distinguishing product quality from educational outcomes is a crucial issue in multimedia development research. A product that receives a positive assessment from a validator does not necessarily lead to greater changes in learning outcomes than learning without that product. Similarly, successfully completing all software test scenarios indicates only that the tested functions operate according to the test criteria. This evidence does not directly explain students' conceptual understanding or their ability to apply knowledge. The study included learning outcome measures to

complement evaluations of multimedia functionality, product ratings, and learning implementation. (Elmoazen et al., 2023; Li & Liang, 2024) show that activity data in digital environments can illuminate the learning process from multiple perspectives. Both studies support using multiple evaluation indicators that complement each other without assuming they are equivalent.

Measuring learning outcomes requires attention to the comparability of instructional conditions. Improvements may occur in both multimedia-supported and conventional instruction; therefore, an increase in the multimedia group alone does not show that multimedia is more effective. In a nonequivalent control-group design, pretest scores describe baseline performance, while changes from pretest to posttest indicate improvement during the instructional period. Comparing these changes can provide evidence of differential improvement, but nonrandom group assignment and possible differences between classes still constrain interpretation. Accordingly, this study distinguishes within-group improvement from evidence of greater improvement relative to the comparison condition.

(Englis & Frederiks, 2024; Lawson et al., 2024) reviewed media comparison studies involving immersive virtual reality in STEM education and highlighted the importance of controlling differences between instructional conditions. Differences in materials, methods, activities, and learner characteristics can shape how researchers interpret comparison results. This consideration is relevant for research involving experimental and control groups. A baseline measurement describes conditions before learning, while a post-learning measurement provides information on performance after learning. Researchers can then compare score differences between the two measurements across groups to assess evidence of differential learning improvement.

In development research, evaluating the product-use process also serves a distinct function. Observations of learning implementation can determine whether planned activities actually occur during multimedia use. This information helps clarify the context in which the intervention is implemented and provides a basis for interpreting learning outcomes. However, implementing all activities does not directly indicate success in achieving learning objectives. An activity can proceed as planned without producing the same changes in ability in all students. Process observations, product ratings, and learning outcome measurements provide different types of evidence and should be interpreted according to their respective purposes. This separation enables more rigorous multimedia evaluation and reduces the risk of drawing conclusions beyond the research data.

Previous research provides a basis for investigating simulation-supported learning in vocational education. (Wibawanto et al., 2022) examined simulation-based interactive multimedia in vocational learning, while (Frady, 2023) reviewed virtual laboratories in engineering technology and vocational education. These studies provide relevant background but do not establish the effectiveness of the product developed in the present study. This study therefore evaluates a web-based multimedia product addressing simple digital circuits in a specific vocational school context. It contributes by examining product functionality, validator ratings, instructional implementation, and learning outcomes as distinct but complementary sources of evidence.

The literature reviewed indicates that simulation technology can support engineering and vocational education, but its implementation results depend on the material context, learning design, and evaluation indicators used. (Wibawanto et al., 2022) examined multimedia simulations for land surveying learning, while (Frady, 2023; Li & Liang, 2024) discussed virtual laboratories in the broader context of engineering education. (Tusher et al., 2024; Yang et al., 2024) examined simulation technology and skills training, while (Elmoazen et al., 2023; Lawson et al., 2024; Mulyati et al., 2022; Reigeluth et al., 2024) emphasized evaluating digital learning environments and comparing outcomes across environments. This literature does not directly explain the results of using the multimedia product developed in this study for Basic Electronics at SMKS Terpadu Bina Insan Mandiri. Therefore, this research provides specific evidence on the product, learners, and learning environment studied, rather than assuming interactive multimedia is a completely new approach.

This study developed web-based interactive multimedia using a four-stage model comprising Define, Design, Develop, and Disseminate. The product addresses Simple Digital Circuits through learning materials, logic-gate simulations, truth tables, circuit and signal visualizations, exercises, and assessment features. The teacher interface supports managing materials, assignments, classes, and learning outcome information. Evaluation combined functional testing, ratings from five validators, observations of learning implementation, and pretest-posttest measurements involving an experimental group and a control group. The study aimed to describe multimedia development, evaluate functional performance and validator ratings, document learning implementation, and examine changes in learning outcomes and differences in mean improvement between groups. Its contribution is contextual: it links product characteristics, implementation, and learning outcomes for the specified digital circuit content while distinguishing technical performance and product ratings from evidence of educational effectiveness.

Method

Research Design and Participants

This study integrated multimedia development with a quasi-experimental evaluation of learning outcomes. Product development followed the four-stage model of Define, Design, Develop, and Disseminate (Rahmawati et al., 2026). We examined learning outcomes using a nonequivalent control-group pretest-posttest design. The participants were 36 Grade 10 students from two existing classes in the Computer and Network Engineering (TKJ) program at SMKS Terpadu Bina Insan Mandiri. Each class comprised 18 students. The classes were selected purposively because they shared the same grade level, vocational program, and minimum mastery criterion (KKM) for the Fundamentals of Computer Network and Telecommunications Engineering subject, specifically the Simple Digital Circuits content. One class used the interactive multimedia as the experimental group, while the other received conventional instruction as the control group. Students were not individually randomized. These selection criteria did not ensure equivalent prior achievement; pretest scores described baseline performance. The assessment focused on Simple Digital Circuits within the specified subject. Therefore, the findings reflect performance on the assessed digital circuit content rather than overall achievement in Basic Electronics.

Multimedia Development and Learning Implementation

The Define stage examined learning needs, student characteristics, practical equipment limitations, and learning objectives for Simple Digital Circuits. The Design stage established the content sequence, navigation structure, logic-gate simulations, truth tables, circuit visualizations, and practice and evaluation features. During the Develop stage, the team built the application using HTML5, CSS3, JavaScript, PHP, and MySQL. The student interface provided learning materials and simulations, while the teacher interface supported managing classes, materials, assignments, and learning outcome information.

Product evaluation combined validator assessments, functional testing, and observations of learning implementation. Dissemination was limited to submitting and demonstrating the application to the teacher at the research school on October 11, 2025. The experimental group used the multimedia to study concepts, explore changes in circuit conditions, and complete exercises. The control group studied the same target content through conventional instruction. Researchers observed implementation in the experimental group during two meetings. Both groups completed pretest assessments before the instructional intervention and posttest assessments after its completion.

Instruments and Quality Control

The instruments comprised a multimedia assessment sheet, functional testing scenarios, learning implementation observation sheets, a multiple-choice test, and an analytical rubric for practical assessment. Five validators rated the multimedia on a five-point scale across four aspects: ease of navigation, material suitability, visual quality and readability, and clarity of user instructions. We summarized their ratings as means and percentages of the maximum possible score. These percentages represent assessments of the specified product characteristics rather than coefficients of content validity.

Functional testing used a black-box approach covering eight scenarios: login, material navigation, logic-gate simulation, circuit visualization, quizzes and evaluation, material management, task management, and learning outcome monitoring. We assessed each scenario by checking whether the function produced the expected output. The resulting evidence was restricted to the scenarios and conditions tested and did not establish performance under all possible usage conditions. Researchers observed learning implementation in the experimental group during two meetings using six activity indicators. The observations recorded whether the specified activities occurred. They documented implementation rather than directly measuring student engagement, conceptual mastery, or learning effectiveness.

We assessed learning outcomes through a written test with 20 multiple-choice items and a practical assessment using an analytical rubric with five indicators. Correct multiple-choice responses received a score of 1, and incorrect responses received a score of 0. We converted written-test scores to a 0-100 scale. Following the school's established assessment policy, we combined the written-test score (weighted at 60%) and the practical-assessment score (weighted at 40%) to produce the final learning outcome score on a 0-100 scale.

Three experts evaluated the relevance of the multiple-choice items using a four-point scale. Item content relevance was quantified using Aiken's V (Aiken, 1985), with coefficients ranging from 0.89 to 1.00. We then piloted the full test with 30 students outside the main sample who shared characteristics similar to those of the study participants. We estimated internal consistency using the Kuder-Richardson Formula KR-20 (Kuder & Richardson, 1937; Yun et al., 2023), yielding a coefficient of 0.87 in the pilot sample. This evidence concerns the content relevance and internal consistency

of the multiple-choice test and does not establish the validity or reliability of the practical-assessment scores or the weighted composite scores.

Data Collection and Analysis

We obtained data from validator assessments, functional testing, implementation observations, and pretest and posttest measurements. Validator ratings were summarized using means and percentages of the maximum possible score. We summarized functional testing and implementation observations as counts and proportions of scenarios or activities meeting the specified criteria. Learning outcome analyses used the weighted composite scores described above. Descriptive statistics included group pretest and posttest means, mean changes, and the standard deviations of individual change scores. We calculated each student's change score by subtracting the pretest score from the posttest score. Paired-samples t-tests examined changes within each group. We used a two-sided Welch's t-test to compare mean change scores between groups without assuming equal population variances (McGee, 2025). We set the significance level at 0.05 and reported the between-group mean difference with a 95% confidence interval. Differences in the significance of separate within-group tests were not treated as evidence of a difference between instructional conditions.

Each instructional condition was represented by only one existing class, preventing us from separating class-related influences from the instructional condition. The student-level t-tests did not account for potential dependence among students within the same class. Welch's correction addressed unequal variances but did not address classroom clustering. Accordingly, we interpreted the statistical comparisons cautiously as exploratory findings from the two classes and did not treat them as evidence of a causal effect of multimedia use.

Results and Discussion

Results

Development of Interactive Learning Multimedia

This study produced web-based interactive multimedia for Grade 10 students in the Computer and Network Engineering (TKJ) program at SMKS Terpadu Bina Insan Mandiri. The product supports Basic Electronics learning through a specific focus on Simple Digital Circuits within the Fundamentals of Computer Network and Telecommunications Engineering subject. Development followed the Define, Design, Develop, and Disseminate stages. The multimedia provides learning resources and interactive activities for students, together with learning management features for teachers.

In the definition stage, development focuses on presenting basic electronic concepts that require visual representation and simulation, especially the relationship between a circuit's input and output conditions. The design stage produces a navigation structure, material presentation, and interface design for students and teachers. In the development stage, validators assess the design, which is realized as interactive multimedia, then functionally test it and use it in learning evaluations. The dissemination stage is reported through the submission and limited demonstration of the multimedia to the research school's teachers on October 11, 2025. Table 1 summarizes the outputs at each development stage.

Table 1. Multimedia Development Results Based on the 4-D Model

Stage	Activity Focus	Development Results
Define	Identification of learning needs and material characteristics	The need for visualization of basic electronics concepts and simulations
Design	Content, navigation, and interface design	Student and teacher interface design
Develop	Product implementation, validator assessment, and testing	Interactive multimedia and product evaluation results
Disseminate	Limited distribution to users	Submission and demonstration of multimedia to teaching teachers

The multimedia was developed using HTML5, CSS3, JavaScript, PHP, and MySQL technologies. The student interface integrates material presentation with logic gate simulations, circuit representations, truth tables, logic expressions, and signal visualizations. These features allow students to observe changes in output based on selected input combinations. The student interface is shown in Figure 1.

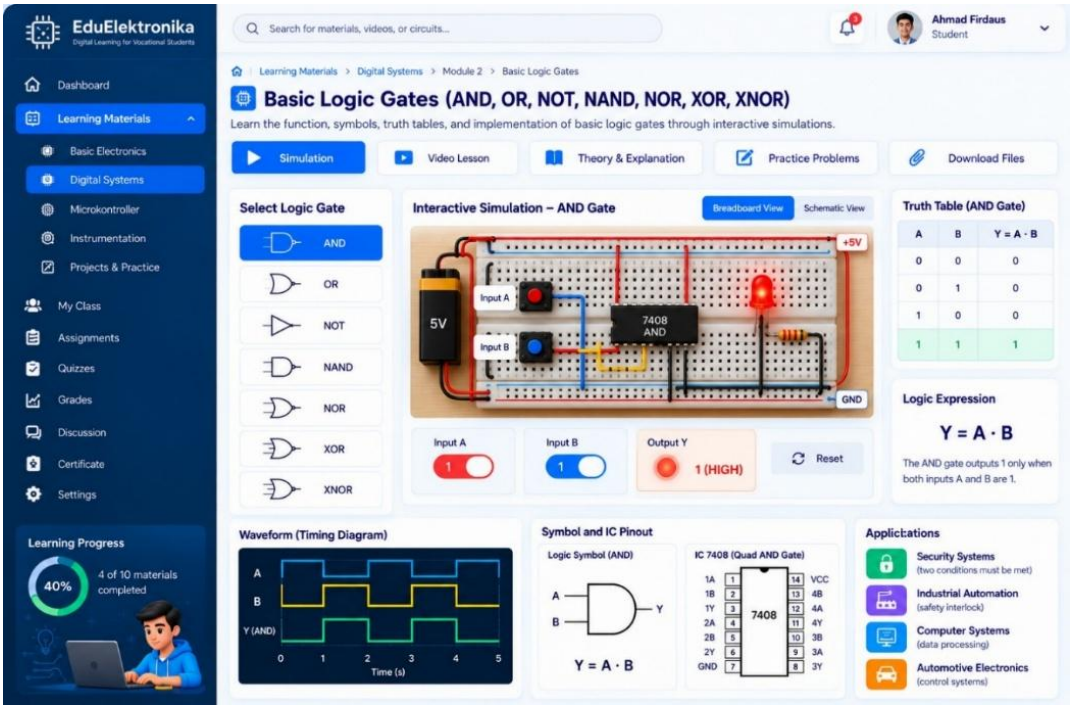


Figure 1. Interactive learning multimedia interface for students

The teacher interface provides facilities for class management, learning materials, assignments, evaluation, and monitoring of learning outcomes. Documentation of the teacher interface is presented in Figure 2.

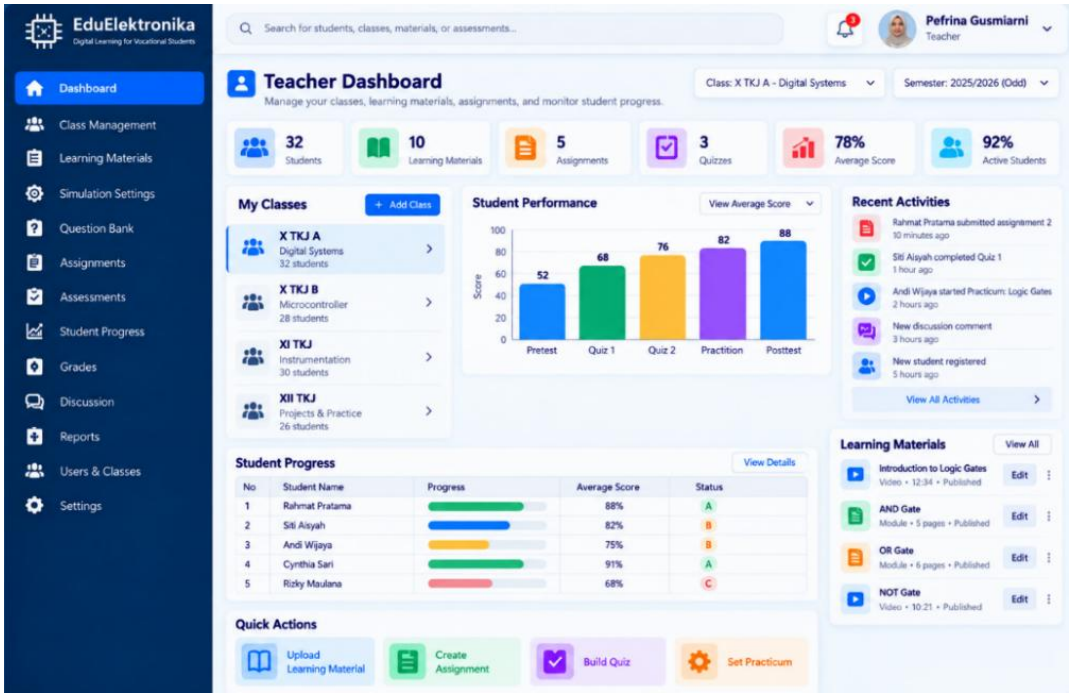


Figure 2. Teacher interface for learning management

Learning Multimedia Functional Testing

We conducted multimedia functional testing using a black-box approach to verify the application's functionality and expected output. Testing covered eight scenarios across the student and teacher interfaces, including user authentication, content navigation, logic gate simulation, circuit visualization, learning evaluation, and learning activity management. Table 2 presents the test results.

Table 2. Results of Functional Testing of Learning Multimedia

No.	Feature	Test Results	Status
1	User login	Dashboard displays according to the account	Succeed
2	Material navigation	The selected material was successfully displayed.	Succeed
3	Logic gate simulation	Output according to truth table	Succeed
4	Circuit visualization	Changes in input conditions are displayed	Succeed
5	Quizzes and evaluations	Answers are processed, and scores are displayed.	Succeed
6	Material management	Material successfully added	Succeed
7	Task management	Task saved successfully	Succeed
8	Monitoring learning outcomes	Student grades are successfully displayed	Succeed

As shown in Table 2, all eight test scenarios passed, resulting in a 100% functional test success rate. These results indicate that the multimedia's primary functions performed as expected under the test scenarios. However, successful functional testing does not, by itself, indicate the multimedia's pedagogical quality or effectiveness in improving learning outcomes.

Validator Assessment

The multimedia assessment involved five validators using four indicators, with scores ranging from 1–5. The indicators assessed included ease of navigation, appropriateness of the material, visual quality and readability, and clarity of the instructions. Table 3 presents the assessment results.

Table 3. Results of Validator Assessment of Learning Multimedia

Indicator	V1	V2	V3	V4	V5	Average	Percentage
Ease of navigation	4	5	4	5	4	4.40	88%
Suitability of material	5	4	5	4	4	4.40	88%
Visual quality and readability	4	4	4	5	5	4.40	88%
Clarity of instructions for use	4	5	3	4	4	4.00	80%
Overall						4.30	86%

The assessment results show that multimedia obtained an overall score of 86 out of 100, with an average of 4.30 on a 5-point scale. Ease of navigation, suitability of material, and visual quality each received 88%, while instruction clarity received 80%. Thus, instruction clarity had the lowest relative score. The assessment results describe the validator's perception of the multimedia characteristics based on the indicators used. The 86% figure represents the proportion of the score to the maximum score and does not directly reflect the level of content validity based on statistical coefficients.

Implementation of Learning Using Multimedia

The study observed learning implementation in the experimental group during two meetings using six activity indicators. Table 4 presents the observation results.

Table 4. Results of Observations on Learning Implementation

Indicator	Meeting 1	Meeting 2
Number of indicators observed	6	6
Implemented indicators	6	6
Indicator not implemented	0	0
Percentage of implementation	100%	100%

Based on Table 4, all learning activity indicators were recorded as having been implemented in both meetings. Implementation reached 100% in each meeting. Observation notes also noted an issue with one computer device during the simulation, but it was reportedly resolved. These results indicate the implementation of the activities according to the observation indicators used, not a direct measure of the quality of learning interactions or student conceptual mastery.

Changes in Student Learning Outcomes

The learning outcome evaluation included 36 students, divided into an experimental group and a control group, each with 18 students. Both groups completed pretests and posttests. We calculated score changes as the difference between each student's pretest and posttest scores. Descriptive statistics for learning outcomes are presented in Table 5.

Table 5. Descriptive Statistics of Student Learning Outcomes

Indicator	Experiment (n = 18)	Control (n = 18)
Pretest average	61.78	57.33
Posttest average	83.33	73.00
Average increase	21.56	15.67
Standard deviation of increase	7.69	10.09

As shown in Table 5, both groups experienced an average increase in learning outcomes after the learning process. The experimental group increased by 21.56 points, while the control group increased by 15.67 points. The difference in average improvement between the two groups was 5.89 points, with the experimental group showing a greater increase. Figure 3 compares the initial and final average scores of the two groups.



Figure 3. Comparison before and after learning between groups

Figure 3 shows that the average posttest scores were higher than the pretest scores in both groups. We then analyzed these descriptive improvements inferentially to determine whether there was statistical evidence of differences in learning outcomes between the groups.

Inferential Analysis of Changes in Learning Outcomes

We used a paired t-test to examine changes within each group and a Welch t-test to compare average improvement between the experimental and control groups. Table 6 presents the test results.

Table 6. Results of Inferential Testing of Learning Outcomes

Testing	t statistics	df	p-value
Pretest-posttest experiment	11.886	17	< 0.001
Pretest-posttest control	6.585	17	< 0.001
Comparison of intergroup improvement (Welch)	1.969	31.77	0.058

A paired t-test showed that the experimental group's change in scores was statistically significant, $t(17) = 11.886$; $p < 0.001$. The change in scores in the control group was also significant, $t(17) = 6.585$; $p < 0.001$. These results indicate a significant increase in scores in each group during the learning period. Comparing the average improvement between the two groups using the Welch t-test resulted in a difference of 5.89 points, $t(31.77) = 1.969$; $p = 0.058$, with a 95% confidence interval of approximately -0.21 to 11.98 points. A confidence interval that includes zero indicates that the data are consistent with no difference in average improvement between the two groups. With a significance level of 0.05, the test results did not show a statistically significant difference in improvement between the experimental and control groups. Therefore, although the experimental group showed a larger descriptive increase in scores, the results do not provide sufficient statistical evidence to conclude that interactive multimedia led to higher learning outcomes than conventional learning.

Discussion

Development of Interactive Multimedia in Basic Electronics Learning

This study developed interactive learning multimedia as a web-based product that integrates material presentation, logic gate simulations, circuit representations, truth tables, and signal visualizations. This integration is pedagogically relevant because learning Basic Electronics requires students to connect abstract concepts with symbolic representations and changes in circuit conditions. In this context, multimedia shows the relationship between logic gate inputs and outputs through representations students can observe directly on the screen. The Cognitive Theory of Multimedia Learning (CTML) explains this product's characteristics. (Mayer, 2024) emphasized that meaningful multimedia learning involves selecting relevant information, organizing verbal and visual representations, and integrating them with prior knowledge. Based on this framework, presenting logic gate symbols, truth tables, and signal visualizations can help students form conceptual relationships if the information is focused and does not overload their cognitive processes.

These results also relate to (Wörner et al., 2022), which showed that combining virtual and real-world experiments can support conceptual understanding in science education. These findings support using simulations to support electronics learning, especially when students need to explore changing circuit conditions before practicing with physical devices.

However, this study has not directly tested the effectiveness of combining digital simulations and physical experiments. (Won et al., 2023) (Paulsen et al., 2024)(Lampropoulos et al., 2024) show that research on immersive learning technology often emphasizes technological features over pedagogical design. This finding reminds us that we cannot judge multimedia development solely on feature completeness. The appropriateness of representation, activity sequence, instruction, and assessment of understanding must be part of the learning design. Therefore, this study's multimedia contribution lies in applying a 4-D model to produce media that connects representations of electronics concepts with simulation facilities and learning management. This contribution is applicative and contextual, not proof that the product has technological or pedagogical superiority over all existing learning media.

Functional Testing, Validator Assessment, and Multimedia Quality

Functional testing showed that all eight reported scenarios performed successfully as intended. These results provide evidence that key multimedia features, including navigation, simulation, evaluation, and learning management, functioned under the test conditions used. However, functional testing success should not be equated with ease of use, user satisfaction, or improved learning outcomes. This distinction aligns with (Ali et al., 2022), which reviewed various interactive laboratory approaches in science education and emphasized the importance of considering both technology design and use in learning activities. While technical success is one component of product evaluation, evidence of learning aligned with its intended use must determine the educational value of technology.

The five validators' assessment yielded an overall score of 86% of the maximum. These results indicate a positive assessment of the multimedia characteristics based on the four indicators used. However, this aggregate score cannot be interpreted as a coefficient of content validity or as direct evidence of learning effectiveness. The validator assessment and the learning outcome measurement provide different information and therefore should be maintained as two separate evaluation components. User instructions received the lowest score among the indicators. This finding has design implications because interactive simulations require instructions that help students understand the activity's purpose, how to transform input, and how to interpret output. (Mayer, 2024) explains the importance of multimedia design that supports processing relevant information, while preliminary research in simulation-based education (Gutierrez et al., 2023; Surbakti et al., 2024) demonstrates the relevance of managing cognitive load in digital learning design.

Although the (Gutierrez et al., 2023) study was conducted in the context of health education, its principles for organizing information and instructions can inform electronic multimedia design. However, this study did not measure students' cognitive load, so we cannot conclude that the available user instructions caused or reduced cognitive load. Therefore, improving the user instructions is a development recommendation directly related to the validator's assessment results. Future development should prioritize clear instructions, consistent terminology, and alignment between simulation steps and learning objectives before adding new features.

Implementation of Learning and the Role of Teachers

Observations showed that all observed activity indicators were implemented in two learning sessions. This finding provides information about implementing multimedia learning procedures under the research conditions. However, activity implementation does not directly reflect the depth of student engagement, the quality of reasoning, or the level of mastery of electronics concepts. (Fadda et al., 2022), A second-level systematic review of virtual and distance learning laboratories in secondary school STEM education found that digital laboratories can support learning and provide benefits when integrated with instructional practices and teacher feedback. These results support the view that simulations should be part of a learning strategy, not simply applications students operate without supervision.

(Rosli & Ishak, 2024; Wörner et al., 2022) also demonstrated the importance of considering the relationship between real-world and virtual experiments. In Basic Electronics learning, this suggests using simulations to introduce concepts, test student predictions, and prepare for practical activities. However, the effectiveness of this sequence remains untested, as this study did not compare multiple integration strategies between simulation and practical activities. Teachers' roles are also relevant, as (Chen et al., 2024; Shahin & Arfaj, 2022) showed that the use of learning technology relates to user factors and institutional conditions. Although this study was conducted in higher education, its findings suggest that multimedia implementation should consider teacher readiness, school support, and the sustainability of technology use. Thus, the learning implementation in this study indicates that multimedia can be used in the observed context. However, broader application requires considering device readiness, procedural clarity, and teacher support in linking simulation activities to conceptual understanding.

Changes in Learning Outcomes and Comparison with Previous Research

Students in the multimedia group showed a statistically significant increase in assessed learning outcomes, with a mean improvement of 21.56 points. This finding documents improved performance during multimedia-supported instruction.

The control group also improved significantly, with a mean increase of 15.67 points. Although the experimental group's mean improvement was descriptively 5.89 points higher, the between-group comparison was not statistically significant, Welch's $t(31.77) = 1.969$, $p = .058$, 95% CI [−0.21, 11.98]. The results therefore show improvement with multimedia use but do not isolate multimedia's contribution or establish its superiority over conventional instruction.

These findings should be interpreted alongside the literature showing simulation's potential benefits in learning. In their meta-analysis of virtual laboratories in science education, (Mera & Benarroch, 2024; Santos & Prudente, 2022) reported a moderate combined effect size on learning achievement. (Li & Liang, 2024) also reported that, based on a meta-analysis of previous studies, virtual laboratories can support engineering education outcomes. The discrepancy between the positive trends in these two meta-analyses and this study's intergroup comparison results should not be interpreted as contradictory. The meta-analysis combined evidence from multiple studies with different intervention characteristics, participants, and implementation conditions, and this study involved 36 students in a single school. Furthermore, the multimedia addressed Simple Digital Circuits within the Fundamentals of Computer Network and Telecommunications Engineering subject for students in the Computer and Network Engineering (TKJ) program. Therefore, its content, learning activities, and assessment differed from those of some virtual laboratories included in the reviewed studies.

These results also align with (Fadda et al., 2022), which showed that learning with virtual laboratories does not always offer clear advantages over other approaches. Its effectiveness may depend on how teachers integrate technology into learning and support students. Therefore, improvements in learning outcomes should be interpreted in the context of the overall learning environment, not just the presence of digital media. Several alternative explanations can be considered. First, conventional instruction provided to the control group may also support improved student understanding. Second, the limited sample size and variation in individual score changes may reduce the accuracy of estimates of intergroup differences. Third, differences in mean initial scores show the importance of accounting for initial ability in comparative analyses. Fourth, instrument characteristics, test-taking experience, and learning conditions may influence measurement results. Both groups improved during the study. Although the experimental group showed a larger mean increase, the between-group estimate remained uncertain, with a confidence interval spanning zero. The findings therefore do not establish that the multimedia produced greater improvement than conventional instruction.

Scientific Contributions and Implications for Learning Evaluation

This research contributes not only to multimedia development but also to using multiple sources of evidence to evaluate the product and its implementation. Functional testing, validator assessments, implementation observations, and learning outcome measurements provide complementary information, but they are not interchangeable as indicators of success. This distinction aligns with (Elmoazen et al., 2023), which showed that learning analytics in virtual laboratories encompasses indicators of student activity, behavior, perception, and performance. This study shows that activity data in digital environments must be interpreted in line with the measurement objectives. The presence of monitoring features in multimedia does not automatically indicate that these features have produced evidence of improved learning outcomes.

(Li & Liang, 2024) emphasize the importance of integrating virtual laboratories with engineering education needs. (Mayer, 2024) suggests explaining multimedia design effectiveness based on the learning processes it supports, not solely on technological sophistication. Both perspectives emphasize the need to evaluate multimedia by linking technological functionality to educational objectives. This study contributes by integrating basic electronics simulations focused on simple digital circuits with a multidimensional evaluation for vocational high school students in the Computer and Network Engineering (TKJ) program. The findings show that positive validator ratings and successful functional testing can coexist with a statistically insignificant difference in learning improvement between groups. This empirical, contextual contribution provides evidence on product quality, learning implementation, and learning outcomes in the setting studied. The study does not establish a new learning theory or demonstrate specific cognitive mechanisms. Instead, it illustrates the importance of distinguishing product quality from comparative educational effectiveness when evaluating interactive multimedia.

Research Limitations and Further Research Directions

This study involved 36 students from two existing classes in a single school, limiting generalization to other vocational education settings. Each instructional condition was represented by one class, so researchers could not adequately separate class-related influences from the instructional condition. Differences in baseline scores and the absence of individual randomization further restrict causal interpretation. The evaluation was limited to simple digital circuits and does not establish effectiveness across basic electronics as a whole. Functional testing covered eight reported scenarios, and implementation observations covered six indicators across two meetings. The study did not assess long-term application stability, learning retention, or transfer to untested practical tasks. Future research should involve multiple

classes per condition, document instructional conditions comprehensively, and account for baseline performance and class-level clustering.

Educational Relevance and Practical Implications

This study's findings are relevant for Basic Electronics teachers, learning media developers, and vocational schools that need alternative ways to present concepts through digital simulations. The developed multimedia can support demonstrations and exercises, particularly by helping students observe the relationships between input and output combinations in logic gates. Combine the multimedia with teacher explanations, prediction activities, truth table interpretation, and practice aligned with learning objectives. This approach aligns with recommendations for integrating virtual and real-world experiences in science and engineering education (Fadda et al., 2022; Wörner et al., 2022). For media developers, the priority for improvement should be clarity of user instructions. For schools, device support and teacher readiness are important to ensure multimedia-based learning can proceed as planned. However, these results suggest that multimedia cannot yet replace conventional learning. Wider implementation requires additional evaluation to ensure its benefits across different student contexts and characteristics.

Conclusions and Suggestions

Conclusions

This study developed web-based interactive multimedia for learning basic electronics, focusing on simple digital circuits in the Fundamentals of Computer Network and Telecommunications Engineering subject for Grade 10 vocational students. All eight reported functional test scenarios passed, validator ratings averaged 86% of the maximum score, and all observed implementation indicators were completed during two meetings. Students in the multimedia group showed a significant increase in assessed learning outcomes, from a mean score of 61.78 to 83.33. The control group also improved significantly. Although the experimental group showed a larger mean improvement, the difference between groups was not statistically significant. These findings document improved performance during multimedia-supported instruction and provide a basis for further product refinement and evaluation. They do not establish that multimedia caused the improvement or outperformed conventional instruction.

Suggestions

Future multimedia development should prioritize clear user instructions and expand functional testing across more diverse usage settings. Teachers can use multimedia to support demonstrations and concept exploration, while still integrating explanations, discussions, and assessment of student understanding. Future research should involve a wider range of participants, clearer group-formation procedures, and consideration of prior analytical skills. Evaluation should be expanded to assess retention of learning outcomes, conceptual understanding, practical skills, and hands-on multimedia experience.

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Author Contributions

Pefrina Gusmiarni contributed to conceptualizing the research, developing the learning multimedia and methodology, collecting and analyzing data, and writing the initial draft of the manuscript. Talia Beater contributed to the research design, interpretation of the results, critical review of the scientific substance, and revision and editing of the manuscript. Both authors reviewed and approved the final version of the manuscript, approved its submission for publication, and take responsibility for the accuracy and integrity of their respective scientific contributions.

Research Ethics and Informed Consent

This research was conducted at Bina Insan Mandiri Integrated Vocational School (SMKS Terpadu Bina Insan Mandiri) involving students from the Computer and Network Engineering program. This research was conducted under Assignment Letter Number 20/LPPM-ST/VIII/2025 dated August 10, 2025, issued by the Institute for Research and Community Service (LPPM), and included research ethics approval in accordance with applicable institutional

authorities and regulations. This research aims to develop interactive learning multimedia and evaluate student learning outcomes. Respondent participation is voluntary, and information collected is limited to learning needs and evaluation of learning outcomes, without involving the collection of sensitive personal data. The study maintains participant confidentiality and data security in accordance with data protection procedures implemented throughout the study.

Conflict of Interest

The authors declare that they have no financial, personal, or professional conflicts of interest that could influence the conduct of the research, analysis, or reporting of the results.

Data Availability Statement

Supporting research data include validator assessment results, multimedia functional testing, learning implementation observations, and student pretest and posttest scores. The article presents the data in the research results table. Furthermore, we anonymized individual data and research instruments, and the corresponding author can provide the instruments upon reasonable request.

Declaration of Generative AI Use

During manuscript preparation, the author used ChatGPT (OpenAI) to assist with language editing, academic narrative structure, and reviews of statistical presentation and calculations based on data provided by the author. The author used Google Translate to translate text from Indonesian to English. These tools do not replace research data collection or verification of statistical analysis. The author checked all translations, calculations, interpretations, citations, and references against the original data and sources. Artificial intelligence tools are not listed as authors. All authors are responsible for the accuracy, originality, confidentiality, integrity, and final content of the manuscript.

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