

Development and evaluation of a 3D electromagnetic field simulation tool for aviation communication engineering education

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ABSTRACT

This study addresses a learning gap in Aviation Communication Engineering education, where electromagnetic field concepts are highly abstract and difficult to understand through conventional teaching methods. Existing instructional media provide limited interactive and contextualized visualizations of electric and magnetic field phenomena, resulting in low levels of students' conceptual understanding. The study employed a Research and Development (R&D) methodology based on the ADDIE (Analysis, Design, Development, Implementation, and Evaluation) instructional design model. Subject matter experts and media experts evaluated the application in terms of content validity, interface design, and interactivity. The primary outcome was the development of a web-based three-dimensional (3D) electromagnetic field simulation to support learning in aviation communication engineering. Its effectiveness was subsequently evaluated using a quasi-experimental pre-test–post-test control-group design involving 30 students assigned to experimental and control groups. The experimental group used the web-based 3D simulation developed with Python and Three.js, whereas the control group received conventional instruction. Data were analyzed using paired-samples t-tests, Cohen's d effect size, and 95% confidence intervals. The results revealed significant improvements in both groups ($p < .001$), with the experimental group demonstrating greater learning gains ($M = 23.3$; from 63.2 to 86.5; $t = -73.06$) than the control group ($M = 11.3$; from 62.8 to 74.1; $t = -48.79$). Effect size analysis indicated a very large educational impact (Cohen's $d \approx 5.85$), while the confidence intervals showed no overlap between groups, supporting the robustness of the observed differences. The findings suggest that 3D simulation-based learning is more effective than conventional instruction in enhancing students' conceptual understanding of electromagnetic field concepts. The study also provides empirical support for the Cognitive Theory of Multimedia Learning and Cognitive Load Theory in the context of vocational aviation education.

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INTRODUCTION

Communication between aircraft and ground stations is vital to ensuring operational safety and efficiency. One of the primary communication systems used is VHF (very high frequency) radio communication, which operates in the 118–137 MHz frequency range. This system utilizes electromagnetic waves to transmit information in real time between aircraft and ground stations. Navigation systems that operate via radio signals (electromagnetic waves) directly generate electric

fields that can affect avionics, communications equipment, and the electromagnetic exposure of the crew (Michałowska et al., 2021). EMI (which originates from electric and magnetic fields at radio frequencies) is one of the main challenges in avionics systems because uncontrolled electromagnetic fields can impact the performance of aircraft navigation and communication systems (Ely, 2005).

Modern communication technologies, including aviation communication systems, rely on electromagnetic waves to transmit information. In aviation, radio-wave propagation characteristics influence air-to-ground communication performance, while electromagnetic interference can affect aircraft radio systems (Leuchter et al., 2021; Okuda et al., 2023). The underlying concepts of electric and magnetic fields, wave propagation, and electromagnetic interactions are often abstract and difficult for students to visualize and understand. This challenge is particularly relevant in vocational education, where students are expected not only to understand fundamental physics concepts but also to connect them with their practical applications in aviation communication systems.

Current learning methods, such as static text and graphics, are clearly inadequate for helping students deepen their understanding of some of the more abstract physics concepts in aviation communications, particularly electric and magnetic fields in aviation communications systems. A more specific example of this is the relationship between magnetic and electric fields and their effects on communications systems. In this regard, the use of visual and interactive learning technologies, such as computer-based simulations, is highly beneficial.

Previous studies have highlighted the potential of simulation-based learning to support students' understanding of scientific concepts by providing dynamic, interactive, and visual representations of phenomena that may otherwise be difficult to explore directly. Almasri (2022), for example, found high levels of student engagement and satisfaction with simulation-supported learning across physics, chemistry, and biology, highlighting the value of computer simulations as an interactive environment for science learning. In vocational education, immersive visual technologies can further connect conceptual knowledge with technical learning experiences.

A systematic review by Chiang et al. (2022) showed that augmented reality has been increasingly applied in vocational training to support the development of vocational skills across a range of training contexts, while Tuwoso et al. (2021) demonstrated the potential of interactive 3D augmented-reality media for supporting vocational learning. Together, these studies indicate that interactive visualization and simulation can provide valuable support for conceptual understanding, student engagement, and the representation of technical knowledge in vocational learning. However, their application to aviation communication education remains limited, particularly for learning abstract electric and magnetic field concepts within the context of aviation communication systems. This gap highlights the need for an accessible and domain-specific simulation that connects electromagnetic concepts with their applications in aviation communication engineering.

Recent studies have demonstrated that simulation-based learning effectively enhances students' conceptual understanding and practical skills in engineering and vocational education. Virtual laboratories, digital twins, mixed reality, and electromagnetic simulation software have been widely adopted to provide interactive learning environments. However, most existing systems are developed for general engineering applications, rely on commercial software, require substantial computational resources, and are not specifically designed for aviation communication engineering education.

Moreover, previous studies primarily focus on simulation implementation and learning outcomes while paying limited attention to instructional design, user needs analysis, curriculum alignment, and web-based accessibility. Existing electromagnetic simulation platforms rarely integrate aviation communication contexts or combine systematic instructional development with expert validation and effectiveness evaluation. These limitations highlight the need for a domain-specific, accessible, and pedagogically sound simulation tool for aviation communication engineering education.

To address these gaps, this study develops a web-based three-dimensional (3D) electromagnetic field simulation specifically for aviation communication engineering education. The application integrates Python for electromagnetic computation and Three.js for interactive 3D visualization and is developed using the ADDIE model, encompassing needs analysis, expert validation, implementation, and effectiveness evaluation through a quasi-experimental design. This

study contributes an accessible simulation-based learning medium and provides empirical evidence supporting the effectiveness of web-based 3D electromagnetic visualization for vocational aviation education.

Table 1. Comparison of Previous Simulation-Based Learning Studies and the Proposed Research

Previous Studies	Main contribution	Remaining limitations	Contribution of this study
Virtual Laboratory	Interactive laboratory activities	Mostly general engineering; limited aviation context	Aviation communication-specific simulation
Electromagnetic Simulation Software	Accurate EM computation	Commercial, expensive, desktop-based	Free web-based 3D simulation
Digital Twin	Realistic system representation	Focus on industrial systems rather than learning	Educational simulation designed for vocational learning
Mixed/Virtual Reality	Immersive learning experience	Requires dedicated hardware	Accessible through standard web browsers
Existing Engineering Simulations	Improve conceptual understanding	Lack of an instructional development framework	Developed using ADDIE with expert validation and effectiveness evaluation

As summarized in Table 1, previous studies have successfully demonstrated the educational benefits of simulation-based learning; however, important gaps remain regarding accessibility, instructional design, domain specificity, and curriculum integration for aviation communication engineering education. Accordingly, this study proposes a web-based 3D electromagnetic field simulation that addresses these limitations by integrating interactive visualization, systematic instructional development, expert validation, and effectiveness evaluation within a single Research and development framework. These characteristics constitute the primary novelty and scientific contribution of the present study.

Addressing this gap, this research aims to design a magnetic and electric field simulation application that will be integrated into aviation communication systems learning. This application aims to provide interactive visualizations that allow students to conduct virtual experiments and closely observe how electromagnetic fields interact in aviation communications. Previous studies have developed various simulation-based learning technologies, including virtual laboratories, electromagnetic simulation software, digital twins, mixed reality applications, and radio communication simulators for engineering and aviation education. Most of these studies have demonstrated that simulation-based learning can effectively improve students' conceptual understanding and practical skills in engineering-related subjects. Despite these advances, several important limitations remain. Most existing simulation tools are designed for general engineering applications, require expensive commercial electromagnetic (EM) solvers, are not web-based, and are not specifically tailored to aviation communication engineering education. In addition, previous studies rarely incorporate systematic user needs analysis into the development process and generally lack interactive three-dimensional (3D) electromagnetic visualizations that are easily accessible to vocational education students.

This study develops a web-based three-dimensional (3D) electromagnetic field simulation tool specifically designed for aviation communication engineering education. The simulation was developed using the ADDIE instructional design model and integrates Python for electromagnetic computation with Three.js for interactive 3D visualization. Furthermore, the development process began with a comprehensive user needs analysis, followed by expert validation involving both subject matter and media experts, implementation, and effectiveness evaluation to ensure the educational quality of the proposed learning media. This study contributes a systematic framework for developing simulation-based learning media that integrates instructional needs analysis, educational design principles, expert validation, implementation, and effectiveness evaluation within a research and development (R&D) approach. In addition to producing an innovative learning medium, this research extends the application of web-based 3D electromagnetic simulation in

vocational aviation education and provides empirical evidence regarding its feasibility and effectiveness in enhancing students' conceptual understanding of electromagnetic phenomena within the context of aviation communication engineering.

Thus, this research provides a significant contribution pedagogically, technologically, and methodologically. Pedagogically, this application seeks to further enhance students' insight and understanding of abstract physics concepts. Technologically, this research produces an application using web technology with Python and Three.js programming to provide interactive 3D visualizations that are easily accessible to students. Methodologically, this research adopts the ADDIE model (analysis, design, development, implementation, and evaluation) to ensure that the resulting product not only improves students' understanding but also optimizes it.

This research focuses on the design and development of a visualization application that helps students understand the basic concepts of electromagnetic systems in aviation communications. This research fills a gap in the existing literature, which previously neglected the use of electromagnetic simulation in the context of vocational education in aviation. This application is expected to be an effective learning tool to improve the quality of education in aviation technology, especially in the understanding of electric and magnetic fields.

METHOD

This study employed a research and development (R&D) approach using the ADDIE model—analysis, design, development, implementation, and evaluation—as the primary framework for developing a web-based three-dimensional (3D) electromagnetic field simulation. The development process began with a needs analysis involving students and lecturers, followed by the design and development of the learning media, expert validation, implementation, and evaluation. Within the evaluation phase, a quasi-experimental pretest–posttest control group design was used to assess the effectiveness of the developed simulation in supporting students' understanding of electric and magnetic fields. Thus, the quasi-experimental design was embedded within the evaluation phase of the ADDIE process rather than employed as a separate research approach.

The study involved 30 students from the Air Navigation Technology Study Program who were enrolled in the Integrated Air Communication Systems and Physics courses. Saturated sampling was used to include all students who met these characteristics. The participants were selected because their prior exposure to physics and air communication provided the disciplinary background needed to engage with the simulation and provide informed feedback on the developed application. Nevertheless, the relatively small and context-specific sample limits the representativeness of the findings beyond the study setting. Future studies could therefore involve broader student populations and employ probability sampling techniques, such as simple random or stratified random sampling, where appropriate.

Data were collected using a concept understanding test, a student perception questionnaire, expert validation sheets, and interviews. Students completed a 20-item multiple-choice test before and after the intervention to assess their understanding of electric and magnetic fields in the context of aviation communication systems. A student perception questionnaire using a five-point Likert scale was administered to obtain students' views of the application, including its ease of use, content feasibility, interactivity, and visualization. Interviews were also conducted with subject matter experts from the physics and aviation communication fields and with media experts, including instructional designers and application developers, to obtain feedback on the content and usability of the application. These sources of evidence were used to examine whether the developed simulation was aligned with the intended learning objectives and suitable for use in vocational aviation education.

Prior to implementation, the web-based 3D electromagnetic field simulation and the research instruments underwent expert validation to assess their content validity and instructional appropriateness. Four validators participated in this process: two subject matter experts in aviation communication engineering and two instructional media experts. Expert judgments were collected using structured validation sheets with a five-point Likert scale ranging from 1 (very poor) to 5 (excellent). The validation instrument comprised 50 assessment items organized into five aspects:

interface design, functionality and navigation, content clarity and suitability of the simulation, visualization and animation quality, and practicality and ease of use. The indicators covered content relevance and accuracy, instructional quality, interface appearance, navigation, usability, interactivity, visualization quality, and technical functionality.

Content validity was assessed using Aiken's V (Aiken, 1985), while the Content Validity Index (CVI) was used to examine agreement among the expert validators (Lynn, 1986). An Aiken's V coefficient of $\geq .80$ was used as the criterion for acceptable content validity (Aiken, 1985), while an S-CVI/Ave value of $\geq .80$ was considered indicative of satisfactory content validity (Lynn, 1986). These procedures were conducted before the simulation was implemented in the learning process.

For the evaluation phase, the students were assigned to experimental and control groups and assessed using a pretest–posttest control group design. The experimental group received the intervention in the form of learning supported by the electric and magnetic field simulation, whereas the control group did not receive the simulation-based treatment. Pretest data were collected before the intervention to establish students' initial understanding of electric and magnetic fields, followed by posttest measurement after the intervention. The research design is presented in Table 2.

Table 2. Pretest–Posttest Control Group Design

Group	Pretest	Treatment	Posttest
Experimental	O ₁	X	O ₂
Control	O ₃	–	O ₄

Note. O₁ and O₃ = pretests administered to the experimental and control groups, respectively; X = learning using the electric and magnetic field simulation application; O₂ and O₄ = posttests administered to the experimental and control groups, respectively.

The quantitative data were analyzed using descriptive statistics, paired-samples t-tests, and normalized gain (N-gain). Descriptive statistics were used to summarize students' pretest and posttest performance. Paired-samples t-tests were conducted to examine whether pretest and posttest scores differed significantly within the experimental and control groups. N-gain scores were calculated to determine the magnitude of improvement in students' conceptual understanding from pretest to posttest. The normalized gain was calculated using Formula 1.

$$g = \frac{\text{posttest score} - \text{pretest score}}{\text{maximum score} - \text{pretest score}} \quad (1)$$

The N-gain scores were interpreted according to Hake's (1998) criteria: $g > .70$ was classified as high, $.30 \leq g \leq .70$ as moderate, and $g < .30$ as low. The pretest–posttest comparisons and N-gain results were used to evaluate changes in students' conceptual understanding following the learning intervention, while the student perception questionnaire and expert feedback provided complementary information regarding the quality, usability, and instructional suitability of the developed simulation.

RESULTS AND DISCUSSION

Results

Needs Analysis

The needs analysis phase was conducted to determine the extent of student needs for the development of electric and magnetic field visualization applications relevant to aviation communication systems material. This analysis was conducted by distributing questionnaires to 30 student respondents who had taken courses related to physics or communication systems. Data were obtained through ten questions that described aspects of conceptual understanding, learning experiences, and expectations for the learning media to be developed. From the results of the questionnaire distributed through the interview instrument, it can be concluded as shown in Table 3.

Table 3. Analysis of Needs for Developing Electric and Magnetic Field Visualization Applications

No.	Aspects Analyzed	Questionnaire Data (Percentage of “Yes”)	Brief Interpretation	Implications for Application Development
1	Difficulty understanding abstract concepts	86.7%	Most students have difficulty explaining the concepts of magnetic fields and electric fields.	Applications need to present concrete visualizations and dynamic simulations to explain abstract concepts.
2	The need for visualization in learning	100%	All respondents stated that visualization helped them understand physics concepts.	The application must display images, animations, and interactive visual models.
3	Limitations of existing learning media	90%	Current media are inadequate to explain magnetic fields and electric fields.	New application-based media that focus on electromagnetic concepts are needed.
4	Support for application development	100%	Students fully support the development of new applications.	Development can continue with a high level of user acceptance.
5	The importance of electromagnetic wave theory	96.7%	This theory is considered essential in aviation communication systems.	Applications need to emphasize the integration between wave theory and its application to aviation communication systems.
6	Experience using application media	26.7%	Only a small proportion have ever used similar learning applications.	Training or user guides are required to make it easier for users to adapt.
7	Expectations for interactive applications	100%	All respondents expected interactive applications for signal propagation/modulation.	The application should provide interactive features and live simulations to allow users to explore concepts.
8	The effectiveness of visual simulation on understanding	96.7%	Nearly all respondents believed simulations improved understanding.	Simulation features need to be designed with an easy-to-use and visually appealing interface.
9	User involvement in development	93.3%	Most are ready to provide input and feedback.	Applications need to undergo user testing as part of formative evaluation.
10	Impact of applications on learning quality	100%	All respondents were optimistic that the application would improve the quality of learning.	The application has the potential to increase the effectiveness of learning and student learning motivation.

Identify the Obstacles Faced

Based on the results of the needs analysis obtained, it is known that most students experience difficulties in understanding the concepts of electric and magnetic fields applied to aviation communication systems. These difficulties are caused by the abstract nature of the material, the limitations of visual and interactive learning media, and the low utilization of digital technology in the learning process. Therefore, the main obstacles were identified, along with applicable solutions and appropriate development strategies, as a basis for designing an effective and interactive electric and magnetic field visualization application.

Table 4. Identification of Constraints, Solutions, and Development Strategies

No. Identified Aspects	Obstacles Faced	Implementable Solutions	Development Strategy
1 Understanding the concept of electric fields and magnetic fields	Students have difficulty understanding abstract theoretical concepts without the aid of visualization.	Developing applications with interactive simulations that illustrate the concept of fields and the direction of lines of force	Using animation and 3D models to explain the relationship between electric current and magnetic fields
2 Availability of learning media	Existing application-based media do not yet cover magnetic fields and electric fields in depth.	Designing new applications that focus on electromagnetic concepts in aviation communication systems	Conducting a comparative study of similar applications and adding visualization features specific to aviation navigation and communication
3 Utilization of technology	A small number of lecturers/students have ever used interactive media due to limited facilities or technological capabilities.	Providing simple usage guides and training related to application utilization	Arranging digital modules and video tutorials so that users can more easily understand how to use the application
4 User participation	Not all active users provide feedback on application development.	Opening a feedback forum or online survey to collect user suggestions and criticism	Involving students and lecturers in the trial stage and testing the effectiveness of the application
5 Quality of learning	The learning materials are still conventional and less interesting to learn.	Combining visual elements, audio, and dynamic simulations to capture students' attention	Implementing a blended learning approach with application integration into the lecture process

Product Design

The design phase focused on translating the learning objectives into the structure and functionality of the application for simulating electric potential in electric and magnetic field contexts. This phase included the design of the user interface, interaction flow, and program architecture to ensure alignment with the intended learning activities. The application was developed as an interactive web-based learning medium that enables students to explore the relationship among electric charge, distance, and electric potential through three-dimensional (3D) visualization. The interface was designed to be simple, responsive, and intuitive, allowing the application to be accessed on both computers and mobile devices.

The application was organized into five interconnected scenes. Scene 1 (Home Page) presents the application title and basic formulas as an introduction to the relevant concepts. Scene 2 (Parameter Input Form) allows users to enter charge (q) and distance (r) values in SI units, with input validation applied to ensure that the values are numeric and non-zero. Scene 3 (Backend Calculation) processes the submitted parameters through the PHP backend, which calls the Python engine to calculate the electric potential; this computational process operates in the background and is not directly displayed to users. Scene 4 (Calculation Results Page) presents the calculated electric potential in scientific notation together with a brief explanation to facilitate interpretation. Finally, Scene 5 (3D Visualization) uses the Three.js library to represent the spatial distribution of electric potential, with variations in color and light intensity indicating the magnitude and sign of the charge.

Visual contrast was incorporated to facilitate interpretation of the simulation. Bright red represents a positive charge, while light blue represents a negative charge, and a color gradient illustrates changes in electric potential with increasing distance. These visual elements were incorporated to support the representation of abstract concepts in more accessible spatial forms,

enabling students to observe how changes in charge and distance are reflected in the simulated electric potential.

Application of Storyboard

Storyboards are used to illustrate the sequence of screens and user interactions within an application. A summary of the main storyboards based on the design results is shown in Table 5.

Table 5. Summary of the Main Storyboard

Scene	Visual Description	Function	User Interaction
1	The home page displays the title and formula ($V = k \cdot q/r$).	Introduction to concepts and initial orientation	No interaction.
2	Parameter input form (q and r) and "Calculate Potential" button.	Take input data from the user.	The user fills in the values and presses the calculate button.
3	The backend (PHP) handles the calculation process and calls the Python engine to perform the computation.	Calculating the electric potential value	Not directly visible to the user.
4	The results page displays potential values and additional information.	Provide numeric results to the user.	Users can read the results or re-enter them.
5	3D visualization shows the central charge and equipotential surfaces.	Provide a spatial representation of electric potential.	Users can rotate, zoom in, and zoom out the display.

Application System Flowchart

The system flowchart illustrates the sequence of processes from user input to the generation of numerical results and 3D visualization. As shown in Figure 1, the process begins when the application displays the initial page and the user enters the electric charge (q) and distance (r) values through the input form. The system then validates the input to ensure that the values are numeric and that the distance is non-zero. If the input does not meet these requirements, an error message is displayed and the user is prompted to revise the entered values.

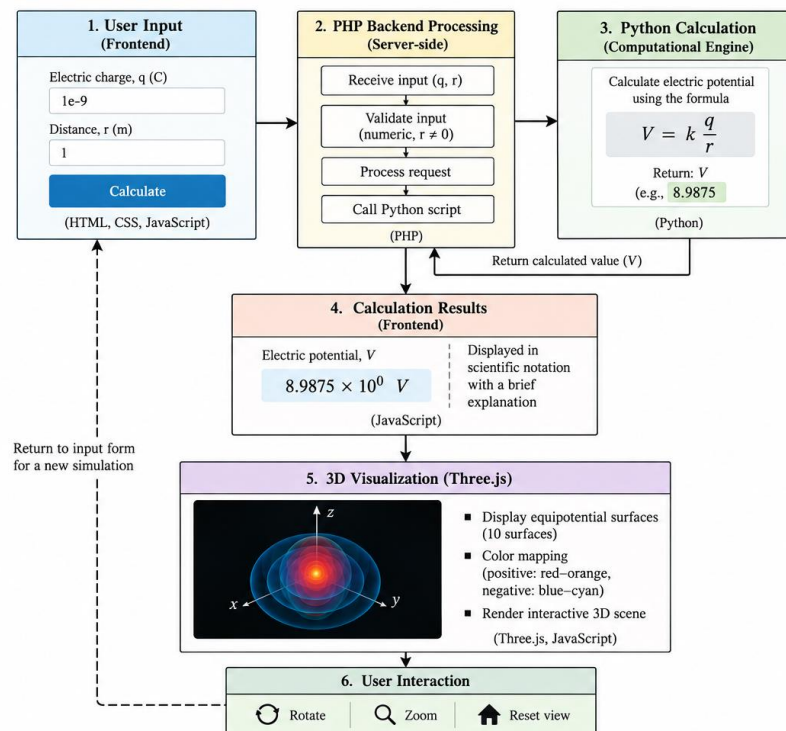


Figure 1. Application System Flowchart

Once the input has been validated, the data are sent to the PHP backend, which calls the Python engine to calculate the electric potential using the specified physics formula. The calculated value is then returned to the frontend and displayed in scientific notation. Subsequently, Three.js renders the spatial distribution of the electric potential as equipotential surfaces, with different colors representing positive and negative potential values. The visualization is interactive, allowing users to rotate, zoom, and reset the view to examine the simulation from different perspectives. After completing the simulation, users can return to the input form and enter new parameter values to initiate another simulation. The overall process is presented in [Figure 1](#).

Application Technical Architecture

The application employs a multilayer architecture comprising three interconnected components: the frontend, backend, and computational engine. The frontend, developed using HTML, CSS, and JavaScript, provides the user interface for entering simulation parameters and displaying the numerical results and 3D visualization. The backend, implemented in PHP, receives and validates user input before passing the required parameters to the Python engine. The Python engine then performs the numerical calculations based on the specified physics formula and returns the calculated values to the backend for subsequent presentation on the frontend. The integration of these components enables the application to process user-defined parameters and generate corresponding numerical and visual outputs within an interactive web-based environment.

Three-Dimensional (3D) Visualization Design

The 3D visualization was developed using Three.js to represent equipotential surfaces as concentric spheres corresponding to constant electric potential values. Visual variations were used to illustrate changes in potential relative to the central charge. The color intensity is greater near the central charge and gradually decreases with increasing distance, while different color gradients distinguish the sign of the charge: red to orange represents positive charges, whereas blue to cyan represents negative charges. The visualization provides a spatial representation of the relationships addressed in the learning material. In particular, it illustrates that electric potential varies inversely with distance from the charge and that equipotential surfaces are perpendicular to electric field lines. It also distinguishes the sign of the electric potential, with positive charges producing positive potential values and negative charges producing negative potential values. By integrating numerical calculations with interactive 3D representations, the application allows students to examine abstract relationships among electric charge, distance, and electric potential within a single visualization environment.

Limited trial results (Alpha Test)

Alpha testing was conducted to evaluate whether the developed electric and magnetic field simulation functioned as intended and met the initial requirements for functionality, visual presentation, and alignment of the learning content with the intended objectives. In development research, internal testing provides an opportunity to identify technical issues and assess product feasibility before broader user testing ([Sugiyono, 2021](#)). This procedure is also consistent with the development approach described by [Gall et al. \(2007\)](#), in which preliminary evaluation is conducted before a product proceeds to wider field testing.

The internal evaluation involved four expert validators, comprising two instructional media experts and two subject matter experts in aviation communication engineering. The media experts evaluated the interface design, navigation, interactivity, usability, visualization, and technical functionality of the application, while the subject matter experts assessed the accuracy and clarity of the physics content and its relevance to aviation communication systems. Expert judgments were collected using structured assessment sheets with a five-point Likert scale. The validation instrument comprised 50 items distributed across five aspects: interface design, functionality and navigation, content clarity and simulation suitability, visualization and animation quality, and practicality and ease of use. The results of the expert validation are presented in [Table 6](#).

Table 6. Expert Validation Results Based on Aiken's V

Aspect	Number of Items	Aiken's V	Category
Interface Design	10	0.856	Very Valid
Functionality and Navigation	10	0.844	Very Valid
Content Clarity and Simulation Suitability	10	0.806	Valid
Visualization and Animation Quality	10	0.863	Very Valid
Practicality and Ease of Use	10	0.806	Valid
Overall	50	0.835	Very Valid

As shown in Table 6, the Aiken's V coefficients for the five assessment aspects ranged from 0.806 to 0.863, with an overall coefficient of 0.835. All coefficients therefore met the validity criterion of $V \geq 0.80$ adopted in this study. Visualization and animation quality obtained the highest coefficient ($V = 0.863$), followed by interface design ($V = 0.856$) and functionality and navigation ($V = 0.844$). Content clarity and simulation suitability and practicality and ease of use each obtained a coefficient of 0.806. These results indicate that all five aspects met the specified content-validity criterion. In addition to Aiken's V, the Content Validity Index (CVI) was used to examine agreement among the expert validators. The resulting I-CVI, S-CVI/Ave, and S-CVI/UA values are presented in Table 7.

Table 7. Content Validity Index Results

Index	Value	Interpretation
I-CVI	0.75–1.00	Valid
S-CVI/Ave	0.850	Good
S-CVI/UA	0.500	Moderate

The S-CVI/Ave value of 0.850 indicated good overall agreement among the expert validators, whereas the S-CVI/UA value of 0.500 was classified as moderate based on the criteria adopted in the study. Taken together, the Aiken's V and CVI results provided evidence that the developed learning media met the specified content-validity criteria and could proceed to implementation following minor revisions based on the experts' recommendations.

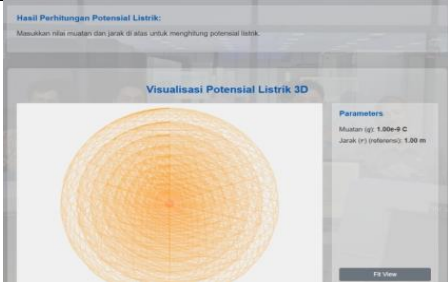
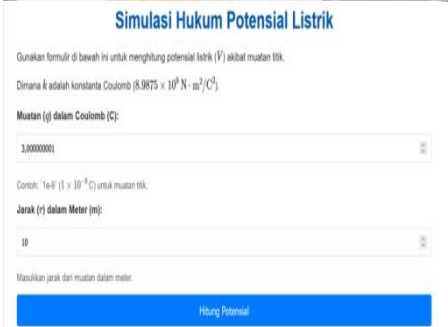
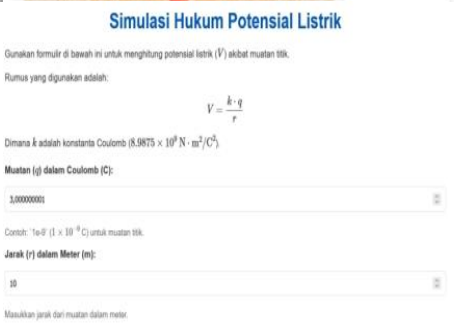
The validation findings are also consistent with previous research highlighting the instructional potential of interactive and simulation-based learning environments. Almasri (2022) found that university students reported high levels of engagement and satisfaction when using computer simulations to learn science concepts, underscoring the value of interactive and visual learning environments. Similarly, Martinez et al. (2021) showed that simulation-based learning can support conceptual understanding by enabling students to visualize processes that are difficult to observe directly and develop more accurate mental models of scientific phenomena. In the present study, visualization and animation quality received the highest validation coefficient ($V = 0.863$), indicating that this component of the simulation was positively evaluated by the expert validators.

Nevertheless, these validation results provide evidence primarily of the content validity and expert-assessed suitability of the developed product rather than its instructional effectiveness. The effectiveness of the simulation in supporting students' conceptual understanding was therefore examined separately during the subsequent field implementation.

Expert Revision

Based on the internal evaluation conducted by two subject matter experts and two media experts, several revisions were made to improve the design and instructional clarity of the electric and magnetic field simulation application. The media experts recommended increasing the contrast between the background and the main visual elements to improve readability. The subject matter experts, meanwhile, recommended adding interactive explanations of the relevant formulas to help students connect the mathematical expressions with their visual representations in the simulation. The revisions made in response to these recommendations are summarized in Table 8.

Table 8. Revisions Based on Media and Subject Matter Expert Feedback

Expert Feedback	Before Revision	After Revision
Media experts recommended increasing the contrast between the background and the main visual elements.		
Subject matter experts recommended adding interactive explanations of the relevant formulas.		

Following the expert review, the application was revised by improving the visual contrast, refining the control buttons, and incorporating interactive textual explanations of the relevant physics formulas, including the Lorentz force, Ampère’s law, and the relationship between electric current and magnetic fields. These revisions addressed the main issues identified during the internal evaluation and improved the visual presentation, usability, and instructional clarity of the simulation. Following these revisions, the application was considered ready to proceed to the implementation stage for further evaluation with students.

Discussion

The findings indicate that the web-based 3D simulation was associated with meaningful improvements in students’ understanding of electric and magnetic field concepts. Students in the experimental group improved from a mean pretest score of 63.2 to a posttest score of 86.5, representing an increase of 23.3 points. The control group also improved, although to a lesser extent, from 62.8 to 74.1, corresponding to an increase of 11.3 points. The N-gain results showed a similar pattern, with the experimental group achieving a gain of 0.63 compared with 0.31 in the control group. According to Hake’s (1998) classification, both values fall within the moderate category, although the experimental group was close to the upper boundary of this range. The paired-samples t-tests further showed statistically significant pretest–posttest improvements within both groups ($p < .001$). Taken together, these findings suggest that students who learned with the simulation demonstrated greater descriptive improvement than those who received conventional instruction.

The improvement observed in the experimental group can be understood in relation to the nature of the concepts addressed in the study. Electric and magnetic fields involve relationships that are difficult to observe directly and are often represented through mathematical expressions and static diagrams. The simulation allowed students to manipulate parameters and examine their corresponding numerical and spatial representations, providing a more concrete way of exploring these abstract relationships. This interpretation is consistent with Alessi and Trollip (2000), who emphasized the role of interactive multimedia in supporting cognitive engagement and conceptual understanding through visual and interactive learning experiences. It also aligns with previous findings showing that visualization and animation can support physics learning (Gustianova et al.,

2024) and that interactive representations can facilitate understanding of complex scientific phenomena that cannot be directly observed (Ainsworth et al., 2020; Prastya & Kurniawati, 2021).

The present findings are also consistent with previous research on simulation-based physics learning. Dantic and Fluraon (2022) reported that PhET simulations supported students' learning of electricity and magnetism by providing opportunities to visualize abstract concepts and engage more actively with the learning material. Similarly, Lahlali et al. (2023) found that interactive simulations were associated with improvements in student motivation, engagement, interaction, and learning outcomes. The current study extends this line of research to the context of vocational aviation education, where electric and magnetic field concepts are relevant to aviation communication systems. Rather than presenting these concepts solely as general physics content, the developed simulation places them within a technical learning context that is more closely related to students' field of study.

The findings can also be interpreted through the Cognitive Theory of Multimedia Learning. Mayer (2009) argues that learning can be supported when verbal and visual information are meaningfully integrated, enabling learners to construct coherent mental representations. In the present simulation, mathematical information was accompanied by interactive 3D representations of electric and magnetic phenomena. This combination may have helped students connect symbolic expressions with spatial representations that would otherwise remain abstract. The needs-analysis findings provide additional support for this interpretation: 86.7% of students initially reported difficulty understanding abstract electric and magnetic field concepts, while all respondents indicated that visualization would be helpful for understanding physics concepts.

Cognitive Load Theory provides another perspective for interpreting the findings. Sweller et al. (2011) explain that instructional design can facilitate learning when unnecessary cognitive demands are minimized and learners' attention is directed toward information that is relevant to understanding the target concept. In this study, the simulation combined numerical calculations, interactive controls, and visual representations within a single learning environment. Such integration may have reduced the need for students to mentally coordinate information presented separately across formulas, static illustrations, and verbal explanations. Nevertheless, the present study did not directly measure cognitive load. Therefore, reduced cognitive load should be regarded as a theoretically plausible explanation for the observed learning improvement rather than as an outcome demonstrated empirically by the current data.

The results of the needs analysis further help explain why an interactive simulation was relevant to this group of learners. Most respondents (90%) considered the existing learning media inadequate for explaining electric and magnetic field concepts, while all respondents supported the development of a new simulation application. In addition, 96.7% regarded electromagnetic wave theory as important to aviation communication systems, indicating that students recognized the disciplinary relevance of the material. These findings support the decision to develop learning media that combine visualization, interactivity, and an aviation-related context. The need for accessible design was also evident because only 26.7% of respondents had previously used similar learning applications. This reinforces the importance of an intuitive interface and clear guidance, consistent with Norman's (2013) emphasis on user-centered design.

From a broader instructional perspective, the findings suggest that interactive 3D simulations can complement conventional instruction in vocational physics education, particularly when students are required to understand relationships that are difficult to demonstrate directly. The pedagogical value of the application lies not merely in replacing static learning materials with digital technology, but in allowing students to explore how changes in physical parameters are reflected in numerical and visual representations. This type of interaction is consistent with constructivist learning perspectives, in which learners develop understanding through active exploration and interaction with learning environments (Jonassen & Rohrer-Murphy, 1999). The strong student support identified during the needs analysis is also consistent with the Technology Acceptance Model (Davis, 1989), particularly the importance of perceived usefulness and ease of use in shaping users' willingness to engage with technology. However, because the present study did not directly test the structural relationships proposed by TAM, the model is used here as an interpretive framework rather than as an empirically tested model.

The development and validation results also provide useful context for interpreting the field implementation. Expert evaluation showed that the simulation met the specified validity criteria, with an overall Aiken's V coefficient of 0.835 and an S-CVI/Ave of 0.850. The revisions made following expert review—including improvements in visual contrast, control elements, and interactive explanations of relevant formulas—were intended to improve the clarity and usability of the application before student implementation. These development procedures are consistent with the broader rationale for simulation-based digital learning described by Koilmo et al. (2025) and with evidence that virtual laboratories and simulations can support conceptual understanding and analytical learning when appropriately integrated into instruction (Darman et al., 2024). Thus, the learning outcomes observed during the field trial should be considered alongside the iterative development and expert-validation processes that preceded implementation.

Several limitations should be considered when interpreting these findings. First, the study involved only 30 students from a single Air Navigation Technology Study Program, with 15 students in each group. The relatively small and context-specific sample limits the generalizability of the findings to other vocational programs, institutions, or student populations. Second, the students were allocated to intact experimental and control groups rather than randomly assigned, as required by the quasi-experimental design used in this study. Consequently, potential pre-existing differences between groups cannot be completely ruled out, even though their mean pretest scores were descriptively similar. Third, the paired-samples t-tests establish significant pretest–posttest changes within each group but do not, by themselves, provide a direct inferential test of whether the magnitude of improvement differed significantly between the experimental and control groups. Therefore, the larger mean increase and N-gain observed in the experimental group should be interpreted primarily as descriptive evidence of greater improvement rather than definitive statistical evidence of superiority over the control condition. Fourth, the study focused on short-term changes in conceptual understanding and did not assess whether the observed improvement was retained over time.

The reported effect-size result should also be interpreted cautiously. Although the experimental group was reported to have a very large Cohen's d value ($d \approx 5.85$), the magnitude is unusually large and should be verified against the calculation procedure and underlying data before strong conclusions are drawn from it. Similarly, the non-overlapping posttest confidence intervals provide information about the estimated posttest scores of the two groups but should not be treated as a substitute for a direct statistical comparison of between-group change. These considerations do not negate the observed improvement but indicate the need for more rigorous comparative analyses in subsequent research.

Future studies could address these limitations by involving larger and more diverse samples across vocational institutions and by using randomized or more rigorously matched comparison groups where feasible. Further research could also apply statistical procedures that directly compare changes between experimental and control groups and examine whether learning gains are maintained through delayed posttests. In addition, the mechanisms underlying the observed improvement warrant further investigation. Measures of cognitive load, student engagement, usability, and technology acceptance could help determine how specific features of the 3D simulation contribute to learning. Extending the application to other technical topics in aviation communication and examining its use across different learning contexts would also provide stronger evidence regarding its instructional applicability.

Overall, the findings provide preliminary evidence that the developed web-based 3D simulation can serve as a useful complementary learning medium for electric and magnetic field concepts in vocational aviation education. The greater descriptive improvement observed in the experimental group, together with the expert-validation results and students' strong expressed need for interactive visualization, supports further development and evaluation of the application. Rather than demonstrating that digital simulation should replace conventional instruction, the findings suggest that carefully designed interactive visualization can enrich existing teaching by making abstract physical relationships more accessible, explorable, and connected to the technical context in which students are expected to apply them.

CONCLUSION

This study developed and evaluated a web-based 3D electromagnetic field simulation designed to support the learning of abstract electric and magnetic field concepts in aviation communication engineering education. The findings showed significant improvements in conceptual understanding in both the experimental and control groups ($p < .001$), with the experimental group demonstrating a greater descriptive improvement than the control group. Students who learned with the simulation increased their mean score from 63.2 to 86.5, with an N-gain of 0.63, compared with an increase from 62.8 to 74.1 and an N-gain of 0.31 in the control group. These findings, together with the expert-validation results, indicate that the developed simulation is a feasible and potentially valuable complementary learning medium for vocational aviation education. By integrating interactive 3D visualization, electromagnetic computation, and an aviation-specific learning context within a systematic ADDIE-based development process, this study contributes a contextually relevant approach to making abstract electromagnetic phenomena more accessible to vocational learners. The findings are also consistent with the principles of Mayer's Cognitive Theory of Multimedia Learning and provide a basis for further investigation of how visually integrated learning environments may support the management of cognitive demands described in Cognitive Load Theory.

The findings should nevertheless be interpreted in light of several limitations. The study involved only 30 students from a single study program, used intact rather than randomly assigned groups, and examined short-term learning outcomes. Moreover, the paired-samples t-tests established significant changes within each group but did not directly test whether the magnitude of change differed significantly between the experimental and control groups. The reported very large effect size ($d \approx 5.85$) should also be verified against the underlying data and calculation procedure before strong conclusions are drawn from its magnitude. Future studies should therefore involve larger and more diverse samples across institutions, employ randomized or rigorously matched comparison groups where feasible, and use statistical analyses that directly compare changes between groups. Long-term retention, cognitive load, learning motivation, engagement, and higher-order thinking skills should also be examined to provide a more comprehensive account of the simulation's educational value. Further development could additionally explore immersive technologies, including virtual reality (VR) and augmented reality (AR), while retaining the accessibility and aviation-specific instructional context of the current web-based application.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : Conceptualization

M : Methodology

So : Software

Va : Validation

I : Investigation

R : Resources

D : Data Curation

O : Writing - Original Draft

Vi : Visualization

Su : Supervision

P : Project administration

Fu : Funding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial or non-financial interests that could have appeared to influence the work reported in this paper.

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