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Development of a Virtual Robotic System for Learning Spatial Vector Concepts in Junior High Schools

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Abstract

This study aims to address the challenges junior high school students often encounter when learning abstract spatial vector concepts. By developing and implementing a virtual robotic system, this research intends to improve students' spatial reasoning, deepen their conceptual understanding, and increase engagement through an interactive, visual, and experiential learning environment that remedies the shortcomings of traditional teaching methods. The system was developed with the Unity Game Engine to deliver 3D visualization, interactive manipulation, and real-time feedback, thereby enhancing conceptual learning. In addition, the instructional design employed the ADDIE model (Analysis, Design, Development, Implementation, Evaluation) to enhance students' understanding of spatial vector concepts. A quasi-experimental design was conducted involving 60 eighth-grade students divided evenly into experimental and control groups. Pre- and post-tests—including achievement assessments, learning attitude questionnaires, and cognitive load scales—were administered to evaluate learning outcomes. The main findings are as follows: (1) The experimental group demonstrated significantly higher learning achievement compared to the control group. (2) Both groups showed improvements in mathematics learning attitudes, with the experimental group exhibiting greater gains in practicality and confidence. (3) Although the experimental group experienced a slightly higher cognitive load, this difference was not statistically significant. (4) The experimental group reported high satisfaction with the system, especially in perceived usefulness. This study demonstrated that integrating virtual reality with the ADDIE model can substantially enhance learners' conceptual understanding and motivation.

Keywords: virtual reality; virtual robotic system; spatial vector concepts; ADDIE model; learning achievement; learning attitudes; cognitive load

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1. Introduction

While Taiwanese students consistently achieve high scores on international mathematics assessments such as TIMSS 2019 [1] and PISA 2022 [2], research reveals a paradox: they often exhibit low interest, low confidence, and high anxiety toward learning mathematics. For instance, TIMSS 2019 revealed that over half of Taiwanese students lack interest in mathematics, and nearly 60% reported low self-confidence—both rates substantially exceeding the international average. PISA 2022 further confirmed that despite ranking third globally in math literacy, Taiwanese students experience elevated math anxiety, which is negatively correlated with their performance.

Among various mathematical topics, spatial vector concepts are notably abstract and challenging, yet they are fundamental to STEM learning and everyday spatial reasoning. Research indicates that strong spatial abilities correlate positively with higher achievement in mathematics, physics, and related disciplines [3,4]. With the rise of 3D digital tools and spatially rich technologies, enhancing students' understanding of vector concepts has become increasingly important. This study investigates the integration of digital tools—specifically a virtual robotic system—into vector instruction. The system offers an interactive, visualized, and immersive learning environment that effectively supports conceptual understanding and student motivation, aligning closely with the essential objectives of technology-enhanced STEM education.

This study aims to develop an interactive learning system that integrates a virtual robotic arm with spatial vector concepts to enhance student engagement and conceptual understanding in mathematics. The system features 3D visualization and interactive tasks, focusing on main topics such as plane vectors, spatial vectors, and coordinate representations. Using a quasi-experimental design, this study compared the learning outcomes of junior high school students who used the virtual robotic system with those who engaged with traditional interactive materials. Specifically, the research investigates:

- The system's impact on students' learning achievement in spatial vector concepts.
- Its influence on students' attitudes toward mathematics.
- Its effect on cognitive load during the learning process.
- Students' satisfaction with the virtual robotic system.

The main objective of this study is to demonstrate the effectiveness of integrating virtual tools in STEM education, highlighting their potential to deepen students' understanding of complex spatial vector concepts and to foster more engaging, interactive, and conceptually meaningful learning environments. The findings can also provide valuable insights for designing technology-enhanced instructional strategies and emphasize the pedagogical benefits of incorporating virtual robotic systems.

2. Materials and Methods

To establish the theoretical foundation for this study, relevant literature was reviewed across five key areas: virtual reality, robotic arms, cognitive load, the ADDIE instructional design model, and spatial vector concepts in mathematics. The review explored how immersive technologies like virtual reality can enhance conceptual understanding, the educational potential of robotic arms for simulating spatial movements, and the critical role of managing learners' cognitive load during instruction. Additionally, the ADDIE model was used to guide the systematic development of interactive materials, while prior studies on spatial vectors have identified common student misconceptions and learning difficulties. These insights collectively informed the design, implementation, and evaluation of the virtual robotic learning system employed in this study.

2.1. Virtual Reality

Virtual reality (VR) is a computer-generated environment that simulates real or imagined experiences through immersive, interactive, and sensory-rich technology. According to Burdea and Coiffet [5], VR comprises three core features—Immersion, Interaction, and Imagination—collectively known as the '3I' characteristics (Figure 1). These elements form the basis of VR's educational potential. Immersion refers to the learner's psychological engagement within a 3D virtual environment, often associated with a state of "flow" where attention is fully absorbed [6]. Interaction emphasizes real-time human-computer communication, allowing learners to manipulate virtual environments via gestures or devices and receive immediate feedback, thereby increasing autonomy and engagement [7]. Imagination highlights VR's ability to visualize abstract or non-existent phenomena, making it especially suitable for conceptual learning in mathematics and science. Collectively, these features establish VR as a powerful tool for enhancing cognitive engagement, motivation, and conceptual understanding in education [8].

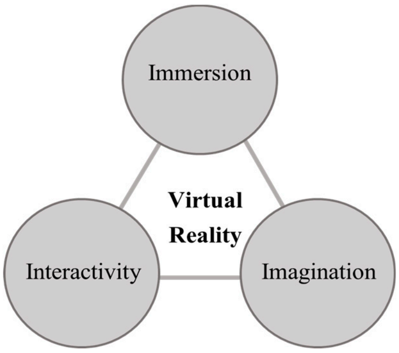

Figure 1. Three core characteristics of virtual reality.

VR environments provide real-time interactivity that fosters increased learner motivation and supports active construction of knowledge. Compared to traditional learning settings, VR offers greater potential for facilitating deeper understanding of complex concepts [9]. Dawley and Dede emphasized that VR can simulate scenarios that are difficult or impossible to realize in the real world, thereby increasing user engagement and learning effectiveness [10]. Immersive experiences enable learners to become fully engaged in the task, enhancing cognitive focus and promoting deeper learning [11]. Additionally, research has shown that VR supports the comprehension of abstract and spatial concepts by visualizing complex information through 3D simulations—an advantage particularly relevant to learning processes involving spatial reasoning [12].

With rapid technological advancement, VR has emerged as a powerful tool for driving educational innovation and learning transformation [13,14]. As a novel digital learning medium, VR introduces engaging and context-rich learning environments that enhance students' understanding and knowledge retention while increasing realism and presence in the learning experience [15]. Unlike traditional instructional models that often rely on one-way knowledge transmission, VR-based environments emphasize learner-centered participation and situational interaction [16]. These immersive settings not only improve memory and comprehension but also stimulate students' interest and motivation, ultimately fostering greater autonomy and active engagement in the learning process [17]. Recent literature highlights the significant educational potential of VR in mathematics instruction, particularly for enhancing spatial and conceptual understanding [18]. Key findings from both domestic and international empirical studies include [19]:

- **Enhanced understanding of spatial concepts:** VR is particularly effective in teaching abstract spatial topics such as geometry and vectors by facilitating visual representation (e.g., 3D vector operations, volume of pyramids).
- **Improved learning outcomes and knowledge retention:** Compared to traditional instruction, VR-based materials (e.g., interactive 3D simulations) significantly boost students' academic performance and long-term memory.
- **Increased motivation and engagement:** Immersive and game-based VR learning environments have been shown to enhance students' interest and active participation.
- **Cross-age applicability:** Studies from elementary to university levels confirm the broad adaptability and impact of VR tools across age groups.
- **Greater support for low-achieving students:** VR interventions have demonstrated particular effectiveness in supporting remedial instruction and differentiated learning for low-achieving students.

In response to the common difficulties faced by junior high school students in learning spatial vectors, this study aims to develop a VR-based learning system tailored to their needs. By integrating immersive and interactive design elements, the system seeks to enhance students' conceptual understanding and learning outcomes in spatial vectors.

2.2. Robotic Arms

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A robotic arm is a mechanical device capable of simulating human arm movements with automated control. It is widely used in performing repetitive or high-precision tasks such as material handling, assembly, and welding in both industrial and non-industrial settings. Typically designed with multiple degrees of freedom, robotic arms can execute complex operations with accuracy and flexibility [20]. With advances in technology and rising labor costs, robotic arm systems have become increasingly sophisticated. A significant milestone was KUKA's introduction of the world's first six-axis industrial robot in 1973, which laid the groundwork for modern intelligent automation [21].

Robotics education plays a critical role in preparing future professionals for careers in technology-related fields [22]. In response to growing industry demands, many higher education institutions have introduced robotics-related courses. Simultaneously, robotics instruction has been adopted in K–12 schools and after-school programs to foster students' logical thinking and creativity. However, traditional industrial robotic arms—despite their high precision and reliability—are often cost-prohibitive, bulky, and pose safety risks, making them impractical for most educational settings.

To address these limitations, compact and affordable desktop robotic arms like the WLkata Mirobot [23] have emerged as feasible alternatives in robotics education. Their lightweight structure, ease of use, and lower operational risk make them well-suited for classroom implementation. Moreover, the development of virtual robotic systems further reduces hardware costs and safety concerns. With the advancement of VR technology, virtual robot-based environments have demonstrated the ability to enhance spatial visualization skills and offer immersive learning experiences, thereby reinforcing the educational value of integrating virtual robotics into instructional activities [24].

This study utilized the WLkata Mirobot (Figure 2), a six-axis desktop robotic arm explicitly designed based on robotics and programming principles, serving as the foundational model for developing the virtual robotic system. As a compact, 6-degree-of-freedom (6DOF) industrial-style robot, the WLkata Mirobot supports multiple control and programming modalities—including remote control, visual programming user interfaces, teaching modes, and gamified interactions—making it highly versatile and effective for robotics and STEAM education [25].

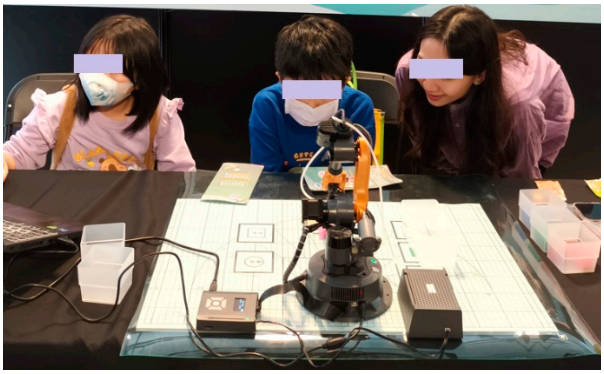

Figure 2. Application of the WLKata Mirobot in STEAM education.

The Mirobot's affordability and versatility make it well-suited for educational and research applications. Its structure includes a base, six rotary joints, an upper arm, a forearm, and an end effector, closely replicating the design of industrial robotic arms. In this study, a full-scale virtual model of the Mirobot (Figure 3) was developed to simulate its operations within a virtual environment. This approach enhances the sense of realism and operational familiarity, while reducing the burden of physical equipment maintenance and ensuring greater feasibility and stability for classroom implementation.

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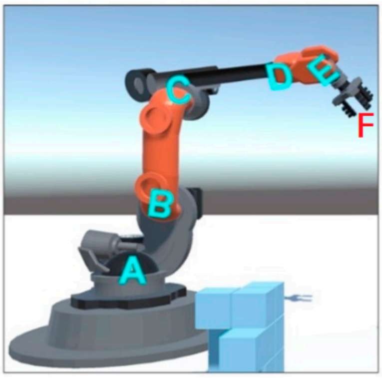

$$A = \begin{bmatrix} c\theta_1 & 0 & s\theta_1 & 29.69c\theta_1 \\ s\theta_1 & 0 & -c\theta_1 & 29.69s\theta_1 \\ 0 & 1 & 0 & 127 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad B = \begin{bmatrix} c\theta_2 & -s\theta_2 & 0 & 108c\theta_2 \\ s\theta_2 & c\theta_2 & 0 & 108s\theta_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$C = \begin{bmatrix} c\theta_3 & 0 & s\theta_3 & 20c\theta_3 \\ s\theta_3 & 0 & -c\theta_3 & 20s\theta_3 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad D = \begin{bmatrix} c\theta_4 & 0 & -s\theta_4 & 0 \\ s\theta_4 & 0 & c\theta_4 & 0 \\ 0 & -1 & 0 & 168.98 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$E = \begin{bmatrix} c\theta_5 & 0 & -s\theta_5 & 0 \\ s\theta_5 & 0 & c\theta_5 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad F = \begin{bmatrix} c\theta_6 & -s\theta_6 & 0 & 0 \\ s\theta_6 & c\theta_6 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The position of the end effector = A·B·C·D·E·F

Figure 3. Simulation of the WLKata Mirobot and its transformation matrices.

2.3. Cognitive Load

Cognitive Load Theory (CLT), initially introduced by Sweller in the 1980s [26], emphasizes the limitations of working memory in processing instructional content. It categorizes cognitive load into three types: intrinsic, extraneous, and germane [27]. Intrinsic load is influenced by the complexity of learning materials and learners' prior knowledge. Extraneous load stems from poor instructional design, while germane load promotes schema construction and deeper learning. Effective instructional design seeks to reduce extraneous load, manage intrinsic load, and foster germane load to enhance learning outcomes.

This study applied CLT to examine learners' cognitive load while interacting with a VR-based learning system. With the increasing use of multimedia and interactive technologies in education, understanding how VR environments impact cognitive processing is crucial for optimizing learning experiences. Cognitive load was measured through three approaches: subjective ratings (mental effort scales), physiological responses (e.g., eye tracking, heart rate, and electroencephalography [28]), and performance-based metrics (e.g., task completion time and accuracy). Among these, subjective measurement was the primary tool due to its simplicity and feasibility in educational research [29].

Previous empirical studies have demonstrated the significant impact of cognitive load on learning performance. For instance, well-designed mobile apps and multimedia systems have been shown to reduce extraneous load and improve learning efficiency, while redundant or poorly integrated information can increase cognitive burden and hinder comprehension [30]. These findings highlight the importance of load-aware instructional strategies, particularly in digital and VR-based learning contexts. Grounded in these principles, our research aims to analyze the types and levels of cognitive load experienced by students during VR-based vector learning tasks. The findings provide implications for designing immersive learning systems that support cognitive processing and improve student outcomes.

2.4. ADDIE Instructional Design Model

This study adopts the ADDIE instructional design model as the framework for developing and implementing the virtual robotic system. Recognized for its clarity, adaptability, and learner-centered approach, ADDIE is one of the most widely applied systematic models in instructional design [31]. Originally developed by [32] for U.S. military training, ADDIE comprises five iterative stages—Analysis, Design, Development, Implementation, and Evaluation—that facilitate systematic and effective instructional design (Figure 4).

- Analysis aims at identifying learning needs, learner characteristics, prior knowledge, motivation, and contextual factors.
- Design outlines instructional objectives, learning strategies, digital tools, and assessment plans based on the analysis.

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- Development transforms designs into tangible materials such as multimedia content, digital tools, and assessment instruments.
- Implementation applies the developed materials in actual teaching settings, including pilot testing and formal instruction.
- Evaluation includes formative (ongoing improvement) and summative (outcome-focused) assessments to ensure instructional quality and learning goal alignment.

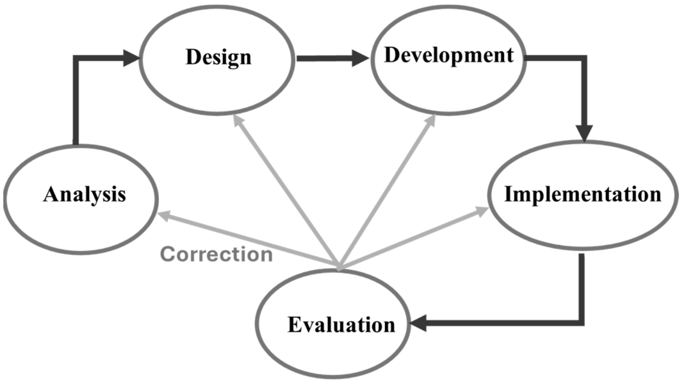

Figure 4. Five stages of ADDIE instructional design model.

Recent studies have consistently demonstrated the ADDIE model's positive impact on learning outcomes across diverse disciplines and educational levels. For example, Jais et al. [33] applied the ADDIE model to develop an interactive self-learning module and effectively enhanced Year 5 students' understanding of English tenses. It validates ADDIE's value in creating engaging, structured materials that improve academic performance and learner autonomy. Based on theoretical and empirical insights [34], the current study employs ADDIE to guide the design of a virtual robotic system. By aligning instructional goals, content complexity, and delivery format, this model ensures a structured, learner-focused, and outcome-driven design process that effectively supports students' understanding of spatial vector concepts using the virtual robotic system.

2.5. Space Vectors

Spatial vectors are fundamental concepts in modern mathematics, characterized by possessing both magnitude and direction, in contrast to scalars. They are essential for representing geometric relationships in space and facilitate the development of spatial reasoning and problem-solving skills. Scholars have proposed various definitions of spatial vectors to emphasize their multidimensional nature. Jeffrey [35] defined spatial vectors as combinations of unit vectors aligned with coordinate axes, while Chisholm [36] traced the conceptual evolution of vectors from physical applications in mechanics and fluid dynamics to their abstract treatment in mathematics. Although high school curricula often focus on complex vector computations such as dot products, cross products, and rotation matrices, this study concentrates on the foundational understanding of spatial vectors. Emphasis is placed on the structure of three-dimensional space, coordinate systems, and basic operations like vector addition to help students build intuitive and practical knowledge.

Spatial ability plays a critical role in learning mathematical concepts involving geometry, vectors, and coordinate space. It refers to the capacity to mentally rotate objects, visualize spatial structures, and reason about spatial relationships [37]. In understanding three-dimensional coordinates, students must mentally construct relationships between axes to accurately locate points and shapes in space [38]. Numerous empirical studies confirm a strong correlation between spatial ability and mathematical achievement. Wai, Lubinski, and Benbow [39] identified spatial skills as a predictor of STEM success, while Cheng and Mix [40] showed that spatial training enhances children's mathematical problem-solving performance. Gunderson et al. [41] further highlighted the importance of spatial representations in tasks involving vectors and transformations. Moreover,

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spatial ability is highly trainable; Uttal et al. [3] demonstrated that it can be improved through physical models, digital simulations, and visualization strategies that support the integration of spatial thinking with mathematical learning.

Despite its importance, learning spatial vectors presents several challenges due to their abstract and three-dimensional nature. Students often struggle to transition from two-dimensional to three-dimensional representations, leading to misinterpretation of vector direction and length. Confusion between points and vectors is also common, as students misapply notations like (1, 2, 3) without understanding the difference between locations and displacements. Furthermore, three-dimensional vector operations are prone to errors related to component calculations and sign conventions, with common misconceptions arising around dot products and angles. To address these challenges, this study employs a virtual robotic system specifically designed to teach spatial vectors for middle school learners. Through visual and interactive activities, the system aims to support learners in constructing accurate spatial understandings, reduce cognitive overload, and enhance both motivation and conceptual comprehension [42].

3. Research Design

This study employed a quasi-experimental research design, dividing participants into two groups for comparative analysis. The experimental group engaged with the virtual robotic system, while the control group used traditional interactive teaching materials. The study aimed to examine the effects of these two instructional approaches on junior high school students' learning effectiveness in spatial vector concepts, attitudes toward mathematics learning, and cognitive load during the learning process.

3.1. Instructional Design

This study adopted the ADDIE instructional design model to direct the development and implementation of an interactive learning system based on the developed virtual robotic arm platform. The ADDIE model consists of five iterative and cyclical stages—Analysis, Design, Development, Implementation, and Evaluation—ensuring continuous refinement until the instructional goals are met.

In the Analysis stage, several challenges in learning spatial vectors were identified. According to international assessments such as PISA and TIMSS, students often demonstrate low motivation and interest in mathematics. Discussions with high school mathematics teachers revealed that spatial vector concepts are abstract and difficult to convey using traditional teaching materials. Questionnaire results revealed that while students had prior experience using online learning platforms, few had engaged with interactive 3D learning tools. Nonetheless, the majority expressed a strong preference for using interactive materials, highlighting their potential educational value. Since the learning content focused on foundational spatial vector concepts, participants were selected from eighth-grade students who had not yet received formal instruction on this topic.

During the Design stage, the instructional content was structured into four major topics: 3D coordinate systems, vector concepts, spatial vectors, and basic rotation concepts, based on national mathematics curricula in Taiwan. The user interface was developed using Canva, an online tool for designing graphics and layouts, to incorporate textbook-aligned visuals and user-friendly layouts. A 15-item spatial vector achievement test was designed, covering multiple-choice, fill-in-the-blank, and contextual problems. All materials were reviewed by experts to ensure content validity and appropriateness.

In the Development stage, the system was built using Unity and Construct 3, designed for desktop operation. Preliminary testing was conducted to ensure system functionality and stability. Mathematics teachers reviewed and refined the instructional activities and assessments to better align with students' abilities and learning objectives.

The Implementation phase adopted a quasi-experimental design. The experiment was conducted over two weeks, with one 50-minute lesson per week (a total of 100 minutes), involving

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8th-grade students from a junior high school in Hsinchu, Taiwan. The instructional process included three stages: a pre-test and review of prior knowledge, interactive lessons with system-based tasks and worksheets, and a post-test to consolidate learning.

In the Evaluation stage, formative assessment was carried out through classroom observation and student worksheet responses. Summative evaluation was based on the pre- and post-test scores of spatial vector achievement. Additionally, mathematics learning attitude and cognitive load questionnaires were administered to assess affective and cognitive impacts. System satisfaction was also measured to evaluate user experience.

By addressing challenges faced by both instructors and learners in spatial vector education, this study intends to evaluate the effectiveness of the virtual robotic system as an interactive digital tool for enhancing conceptual understanding, learner motivation, and instructional outcomes through a comprehensive quantitative analysis.

3.2. Research Structure

This study aims to investigate the effects of integrating an interactive virtual robotic system into junior high school mathematics instruction on students' spatial vector learning performance, mathematical learning attitudes, and cognitive load. A quasi-experimental design with a single independent variable was adopted. Participants were divided into two groups (30 students in each group) based on the learning method: the experimental group used the virtual robotic system, while the control group received instruction through traditional interactive materials. Research instruments included a spatial vector achievement test, a mathematics learning attitude scale, a cognitive load scale. These tools were used to compare the two groups in terms of learning outcomes, attitude changes, and cognitive load differences. The research variables of this study are shown in Figure 5.

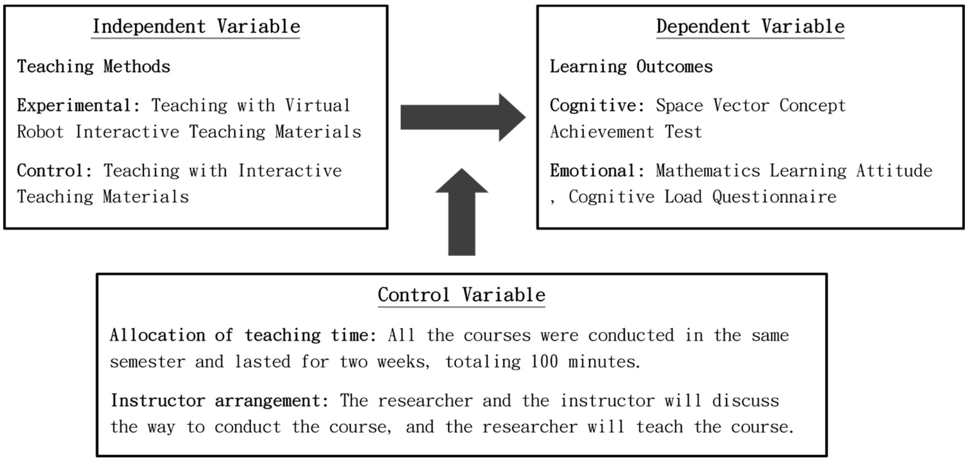

Figure 5. Research framework and variables of the study.

In this study, both the experimental and control groups received the same instructional content and followed an identical course schedule. The key difference was that the experimental group used the virtual robotic learning system in addition to the standard materials. This system provided an interactive 3D environment where learners could manipulate a virtual robotic arm to observe changes in coordinates and vectors within three-dimensional space. By enabling direct interaction and visualization, the system aimed to enhance students' understanding of spatial vector concepts and improve the accessibility of abstract mathematical concepts through concrete and dynamic representations. The experimental design framework for this research is described in Table 1.

Table 1. Experimental design framework for this research.

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Group	Pre-test	Experimental Processing	Post-test
Experimental Group	X1, Q1	T1	X2, Q2, Q3
Control Group		T2	

- X1: Both groups took the same pre-test of the achievement test.
- Q1: Both groups took the same pre-test of learning attitude questionnaire.
- T1: Students in the experimental group participated in the lesson using the virtual robotic system integrated with spatial vector teaching materials.
- T2: Students in the control group received traditional instruction using interactive spatial vector teaching materials.
- X2: Students in both groups took the achievement test (post-test).
- Q2: Both groups took the same post-test of learning attitude questionnaire.
- Q3: Both groups were surveyed on cognitive load and system satisfaction.

3.3. Research Participants

Although the instructional content in this study was based in the high school mathematics curriculum on spatial vectors, the materials were limited to fundamental concepts such as 3D coordinates, vector representation, and basic operations, while more advanced topics were excluded. During the pilot phase, the system was tested with ninth-grade students who demonstrated strong comprehension of the content and satisfactory learning outcomes. These findings suggest that the material was appropriately challenging and can be feasibly adapted for eighth-grade junior high school students.

Accordingly, the formal experiment was conducted with two eighth-grade classes from a junior high school in Hsinchu, Taiwan. The two classes were randomly assigned to an experimental group and a control group. The intervention lasted two weeks, with one 50-minute lesson per week, totaling 100 minutes of instruction (Table 2). Due to constraints such as school location, class scheduling, teacher availability, and institutional willingness, cross-school or cross-class sampling was not feasible. Therefore, intact classes were used and randomly assigned to experimental conditions. This study employed a quasi-experimental design with a single independent variable to examine the effects of the instructional intervention on students' learning performance between the two groups.

Table 2. Participant numbers and gender distribution in the two groups.

Group	Male	Female	Total
Experimental Group	15	15	30
Control Group	13	17	30
Number of Students	28	32	60

3.4. Research Tools

This study developed an interactive virtual robotic system to support the learning of spatial vector concepts within the junior high school mathematics curriculum. The learning content encompasses key topics such as three-dimensional coordinate systems, vector representations, and vector addition, with the aim of enhancing students' conceptual understanding through interactive and visually enriched learning experiences. The system employed Blender for modeling a six-axis robotic arm based on the real-world specifications of the WLKATA Mirobot and utilized Unity Game Engine and Construct 3 as development tools to implement interaction logic and instructional sequences.

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The virtual robotic arm was constructed at a 1:1 scale, allowing students to simulate movements along the X, Y, and Z axes and effectively visualize transformations in 3D space. The instructional design comprises four structured learning tasks:

- Spatial Coordinates – understanding points in 3D space.
- Vector Concepts – interpreting vector meaning and operations.
- Rotation Concepts – predicting coordinate changes after spatial rotation.
- 3D Vectors – learning vector addition and position vectors in space.

The virtual environment enables students to manipulate the robotic arm and observe spatial changes in real time, fostering spatial reasoning and abstract mathematical thinking through active manipulation and visual observation.

3.5. System Development

The virtual robotic system developed in this study was structured around four core tasks aligned with the learning progression and stages of cognitive development: (1) Spatial Coordinates, (2) Vector Concepts, (3) Rotation Concepts, and (4) Spatial Vectors. Each task incorporated interactive activities and instructional content designed to progressively guide students from fundamental spatial positioning to the contextual application of spatial vector concepts.

3.5.1. Learning Objectives and User Guide

The system's main page clearly outlines the learning objectives and provides a user guide (Figure 6), ensuring that learners are familiar with the system's operation before engaging in the interactive learning tasks. The system adopts a combination of goal-oriented and action-based learning design, enabling learners to navigate tasks independently while remaining guided by a structured instructional framework. In addition, printed learning worksheets were incorporated to provide instructional support, promote reflection, and document the learning process, thereby helping learners connect virtual interactions with mathematical concepts and enhance overall learning outcomes.

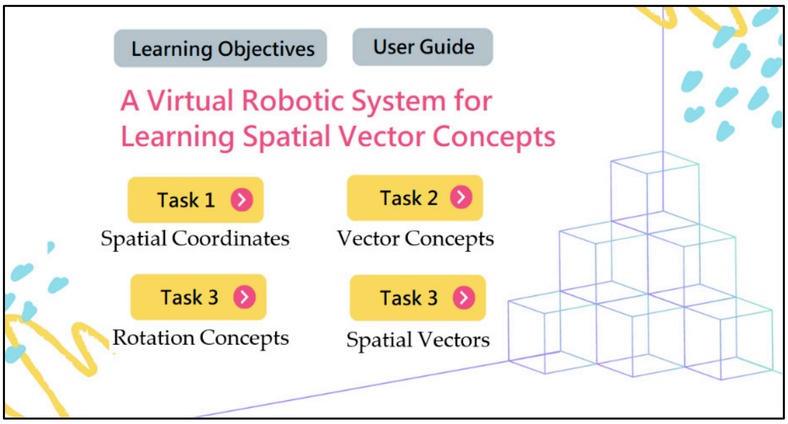

Figure 6. Learning objectives and user guide of the virtual robotic system.

3.5.2. Learning Materials

To support students' self-directed learning and conceptual understanding, the system includes embedded learning materials aligned with the core mathematical concepts of each task. These materials were adapted from high school mathematics textbooks and modified to match the system's instructional goals. Accompanying printed worksheets enable learners to preview key concepts and reinforce understanding before and after interacting with the virtual robotic system through guided reading and practice exercises. Each knowledge section is structured according to the learning objectives of the corresponding task and is subdivided into thematic subtopics.

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The layout of the learning materials is designed for clarity and logical organization, enabling easy navigation and supporting learners in tracking their progress. Each subsection engages learners with worksheet-based questions designed to reinforce comprehension and foster active participation. Additionally, the system features a "lightbulb" function that learners can click to access hints or supplementary explanations during problem-solving. This feature supports content comprehension and encourages the development of strategic thinking skills. The integration of textual guidance, interactive engagement, and scaffolded support offers a balanced learning experience that fosters both learner autonomy and conceptual clarity. Through structured interaction with the virtual robotic system and guided learning activities, students are better equipped to internalize spatial vector concepts and enhance their overall learning outcomes.

3.5.3. Learning Tasks

After learners engage with the learning materials to understand fundamental concepts of spatial vectors, the system guides them into corresponding interactive environments to complete the learning tasks and reinforce their mathematical understanding. Each interactive space aligns with its task, providing realistic scenarios and clear instructions that guide students in exploring and working interactively within a 3D virtual environment. Each user interface features functional buttons in the upper-right corner, offering quick access to support tools such as vector visualization, coordinate information, and operational hints. If learners encounter difficulties during the activity, they can click the "question mark" icon to access real-time guidance and explanatory prompts, ensuring a smoother learning experience and fostering self-directed participation. The interactive modules emphasize the integration of conceptual understanding with procedural practice, allowing abstract concepts such as spatial coordinates and vector transformations to be visualized and explored in a concrete, dynamic format. To further support learners, the system provides interface illustrations and operational guides that explain the purpose, structure, and functions of each interactive task space.

- **Task 1: Spatial Coordinates**

This task is designed to help learners develop a fundamental understanding of the three-dimensional coordinate system, emphasizing the geometric meaning and interrelationships among the X-, Y-, and Z-axes. To visualize this abstract concept, the system presents a 3D virtual environment featuring clearly defined axes and grid lines, allowing learners to perceive spatial structure and point positioning intuitively. Learners interact with a cube object by manipulating its vertices in space to observe corresponding changes in coordinates. This hands-on experience strengthens their understanding of the relationship between point locations and numerical values in 3D space.

In addition, the system includes a built-in assessment activity in which learners are instructed to move a specific vertex of the cube to a given coordinate. This target-positioning exercise enhances learners' spatial accuracy and supports the development of basic skills in coordinate transformation and spatial estimation. Learners can use the arrows next to X, Y, and Z to adjust the square's position on the screen. They can click the (X,Y) button to display the coordinates of the current point A and point B. After pressing the confirmation button, a feedback message immediately appears to inform learners whether point A has been moved to the correct position (Figure 7).

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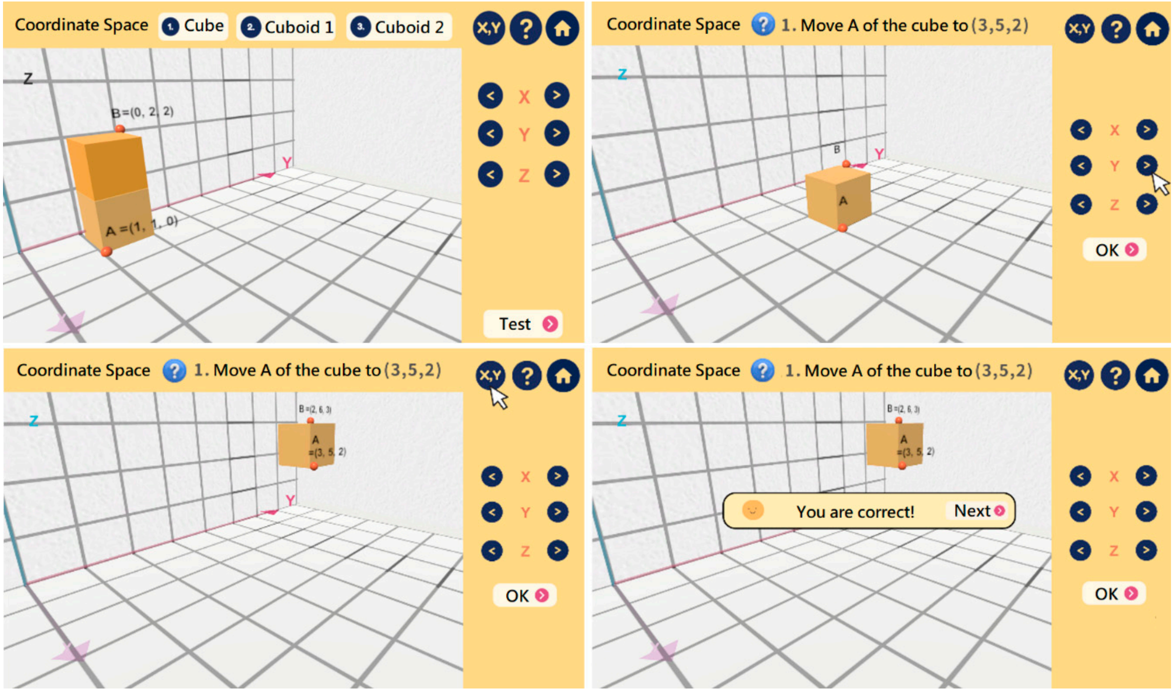

Figure 7. Exploring coordinate space through interactive moving operation.

- **Task 2: Vector Concepts**

This task is designed to help learners develop the basic concepts of plane vectors and understand the correspondence between vectors and coordinate points. Through visualizing the movement of a virtual robot in a 2D plane, the interactive operation allows learners to directly observe the changes in the vectors generated when the robotic arm moves between different coordinate points. Through such operations, learners can gradually understand the direction and magnitude of spatial vectors, as well as the geometric meaning of their differences with the coordinates and their slopes in various problem-solving contexts, enhancing overall mathematical reasoning skills.

In the "Verification" phase, learners engage in vector addition through interactive reasoning and manipulation. The system presents a sequence of points (A→B→C→D→ E) and guides learners to compute the cumulative sum of vectors: $\overrightarrow{AB}+\overrightarrow{BC}+\overrightarrow{CD}+\overrightarrow{DE}$, and verify whether it equals the direct vector $\overrightarrow{AE}$. This activity not only reinforces the computational rules and geometric interpretation of vector addition but also enhances learners' conceptual understanding of a vector as a cumulative displacement from the starting point to the endpoint. Through visual representation and hands-on interaction, learners deepen their understanding of vector chaining and total displacement in three-dimensional space. When learners drag the scroll bars to adjust the joint angles with the mouse, the corresponding robot arm axis on the screen rotates accordingly, as shown in the upper part of Figure 8. Pressing the Vectors button $(\overrightarrow{AB})$ displays all vectors and their slopes. Learners can click any line segment to highlight the corresponding vector (in red) along with its coordinate values, as shown in the lower part of Figure 8.

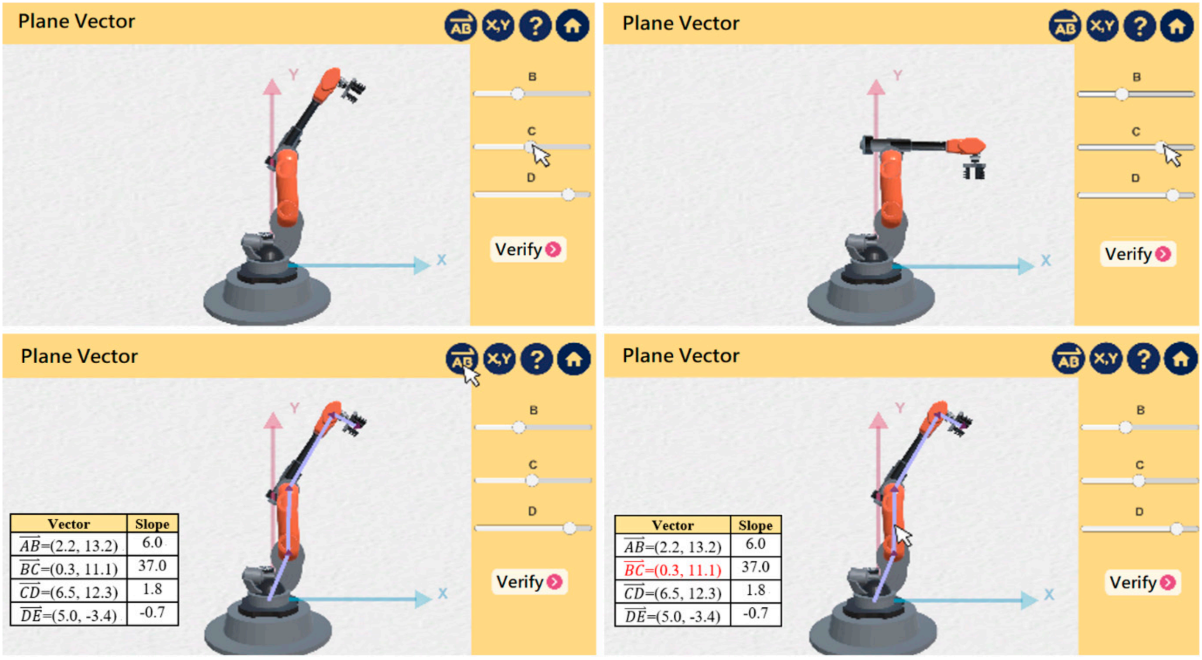

Figure 8. Visualizing vector concepts through continuous manipulation.

- **Task 3: Rotation Concepts**

This task is designed to help learners understand how rotating an object in three-dimensional space affects its coordinate values and spatial orientation. Unlike previous tasks, the individual axis angles of the virtual robot are fixed and cannot be directly adjusted. This constraint encourages learners to concentrate on observing and reasoning about the robot's overall rotational movement within the 3D space. The virtual robot is initially positioned at the origin of the coordinate system. Learners can rotate the entire robot model to observe changes in its direction and coordinate position. This rotation simulates real-world spatial transformations, allowing learners to understand how changes in object orientation correspond to adjustments in three-dimensional coordinates.

In addition to observing rotation, learners can also adjust the virtual robot's position to explore object displacement within the 3D coordinate system. This task emphasizes the development of spatial awareness and relative positioning, guiding learners to construct an understanding of direction and location in 3D space. Through interactive manipulation, learners strengthen spatial visualization and reasoning skills—serving as foundational experience for understanding the application of spatial vectors (Figure 9).

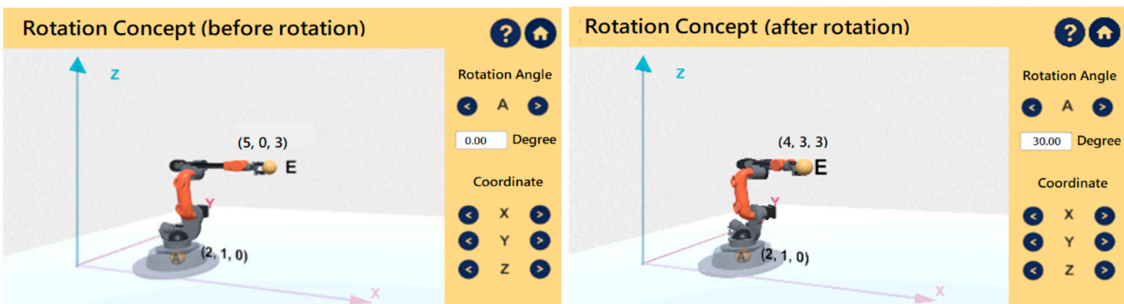

Figure 9. Visualizing rotation concept through continuous manipulation.

- **Task 4: Spatial Vectors**

This task represents the final stage of the learning activity, with the primary goal of integrating concepts from previous tasks—spatial coordinates, vector representation, and rotation—to enhance learners' understanding and application of spatial vectors in three-dimensional space. Compared to Task 2, which focuses on planar vectors, this task introduces more advanced features. Learners can manipulate both the rotational angles of individual robot axes and the overall orientation of the virtual robot, allowing them to fully observe and control changes in spatial coordinates and directionality.

During the interactive process, learners observe how the virtual robot's rotation and displacement in 3D space results in changes to its joint coordinates. This helps them understand the relationship between the start and end points of a vector and construct a conceptual framework for spatial vector representation. In the "Assessment" phase, a goal-oriented task is presented: learners must manipulate the virtual robot to change the direction and position of point E (the end effector) to contact a designated target block. Learners can adjust the angles of A, B, C, and D axis points to control the movement of the virtual arm, guiding its end to touch the square. Upon successful contact, the system displays the target's coordinates, providing immediate feedback on the learner's spatial estimation and vector reasoning skills. This task consolidates previously learned concepts while introducing greater complexity, effectively enhancing learners' understanding and operational proficiency with spatial vectors in a three-dimensional environment (Figure 10).

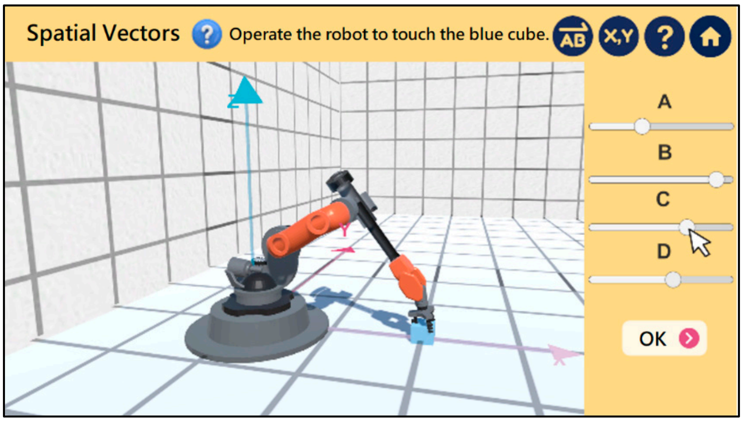

Figure 10. Understanding spatial vector concepts through interactive operation.

3.6. Statistical Methodologies

This study utilized quantitative methodologies to empirically investigate the effects of the virtual robotic system on students' spatial vector learning outcomes, mathematics learning attitudes, and cognitive load. Experimental results were collected using the Spatial Vector Achievement Test, Mathematics Learning Attitude Scale, Cognitive Load Scale, and System Satisfaction Survey. All data were coded and analyzed using IBM SPSS Statistics 20, with hypothesis testing conducted at a significance level of $\alpha = 0.05$. The statistical methods employed are detailed in the following section.

- **Descriptive Statistics:** Descriptive statistics were used to summarize the mean and standard deviation of each variable, offering an overview of students' performance and psychological responses before and after the instructional intervention.
- **Paired-Samples t-Test:** Paired-samples t-tests were conducted to compare the pre-test and post-test scores within both the experimental and control groups. This analysis examined whether there was a statistically significant improvement in learning achievement and mathematics learning attitude following the intervention.
- **One-Way ANCOVA:** a one-way ANCOVA was performed using the pre-test scores as covariates and the post-test scores as dependent variables. This method controlled for initial group differences and allowed for a more precise comparison of the instructional effects between the experimental and control groups.

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- **Independent-Samples t-Test:** Two independent-samples t-tests were used to analyze group differences in cognitive load and system satisfaction.

4. Results

This study adopted a quasi-experimental design to explore how a virtual robotic system influences junior high school students' spatial vector learning. Two groups were compared: the experimental group used the virtual robotic system, while the control group engaged with standard interactive learning materials. The study examined differences in four areas—learning achievement, mathematics learning attitudes, cognitive load, and system satisfaction, as detailed in the following sections.

4.1. Analysis of Learning Achievement

The participants in this study consisted of two intact junior high school classes, which were randomly assigned to the experimental group and the control group, each with 30 students. None of the students had prior experience with spatial vectors; their only previous exposure was to the 2D coordinate system taught in the first year of junior high school. To examine the effect of different instructional media—specifically, the integration of a virtual robotic arm in the interactive learning system—both groups completed a Spatial Vector Achievement Test before and after the intervention. The test included 7 multiple-choice questions (7 points each), 3 fill-in-the-blank questions (7 points each), and 2 item sets (5 sub-questions per set, 6 points each), for a total of 100 points.

As shown in Table 3, the experimental group improved from a pre-test mean of 49.37 ($SD = 22.33$) to a post-test mean of 75.87 ($SD = 25.02$). The control group increased from a pre-test mean of 45.17 ($SD = 25.70$) to a post-test mean of 62.43 ($SD = 27.70$). Both groups showed significant improvement; however, the experimental group achieved greater gains with less score variability, suggesting more consistent and effective learning outcomes across diverse student ability levels.

Table 3. Descriptive statistics on pre-test and post-test scores for the two groups.

Group	Pre-test		Post-test	
	Mean	SD	Mean	SD
Experimental Group	49.37	22.33	75.87	25.02
Control Group	45.17	25.70	62.43	27.70

Further analysis using paired-sample t-tests (Table 4) revealed that both groups showed statistically significant improvements in post-test scores. The experimental group demonstrated a mean gain of 26.500 ($SD = 13.873$), with a t-value of 10.462 ($p < 0.001$), while the control group showed a mean gain of 17.267 ($SD = 17.235$), with a t-value of 5.487 ($p < 0.001$). These results indicate that while both instructional approaches led to significant learning gains, the experimental group—which used the virtual robotic system—achieved a greater improvement in spatial vector understanding compared to the control group. However, since initial performance levels differed between groups, an ANCOVA was conducted to control for pre-test scores and allow for a more accurate comparison of instructional effectiveness between the two groups.

Table 4. Results of paired-samples t-test on learning achievement for both groups.

Source	Mean	SD	t	*p*
Experimental Group	26.500	13.873	10.462	< 0.001***
Control Group	17.267	17.235	5.487	< 0.001***

***$p < 0.001$.

Prior to conducting ANCOVA, the homogeneity of regression slopes was tested. As shown in Table 5, the interaction between group and pre-test scores was not significant ($F = 0.209$, $p = 0.649 > 0.05$), satisfying the homogeneity of regression slopes assumption and thus permitting the use of ANCOVA to compare group outcomes.

Table 5. Testing the homogeneity of regression coefficients within groups.

Source	Type III Sum of Squares	df	F	p	Eta squared
Pre-test	26423.803	1	107.715	0.000	0.658
Group	103.202	1	.421	0.519	0.007
Group*Pre-test	51.378	1	.209	0.649	0.004
Error	13737.503	56			
Total	3300017.000	60			

The results of ANCOVA (Table 6) show a significant effect of instructional group on students' post-test scores after controlling for pre-test performance ($F = 5.783$, $p = 0.019 < 0.05$). This indicates that the type of instructional media had a statistically significant impact on learning outcomes. Specifically, students using the virtual robotic system demonstrated greater improvement in spatial vector achievement compared to those who used the standard interactive materials.

Table 6. ANCOVA results on learning achievement for both groups.

Source	Type III Sum of Squares	df	F	p	Eta squared
Pre-test	26617.952	1	110.032	0.000	0.659
Group	1398.958	1	5.783	0.019*	0.092
Error	13788.881	57			
Total	330017.000	60			

*$p < 0.05$.

4.2. Analysis of Mathematics Learning Attitudes

This section analyzes changes in students' mathematics learning attitudes before and after the instructional intervention. The attitude scale consisted of 17 items across five dimensions: Practicality, Confidence, Motivation, Strategy Use, and Help-Seeking. Descriptive statistics (Table 7) indicated that both groups showed improvements. The experimental group had a pre-test mean of 3.27 (SD = 0.55) and post-test mean of 3.58 (SD = 0.72), while the control group improved from 3.22 (SD = 0.77) to 3.45 (SD = 0.14). The experimental group's scores were slightly higher than those of the control group, suggesting a more pronounced shift in learning attitudes. Paired-sample t-tests (Table 8) further revealed statistically significant improvements in mathematics learning attitudes for both groups. This suggests that regardless of the instructional medium, the intervention positively influenced students' attitudes toward mathematics, enhancing their engagement and willingness to persist in mathematical problem-solving.

Table 7. Descriptive statistics on pre-test and post-test mathematics learning attitudes.

Group	Pre-test		Post-test	
	Mean	SD	Mean	SD

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Experimental Group	3.27	0.55	3.58	0.72
Control Group	3.22	0.77	3.45	0.14

Table 8. Results of paired-samples t-test on mathematics learning attitudes for both groups.

Group	Mean	SD	t	p
Experimental Group	0.31	0.53	3.24	0.003**
Control Group	0.23	0.41	3.06	0.005**

**p < 0.01.

The ANCOVA results (Table 9) revealed that the instructional group did not have a statistically significant effect on students' overall mathematics learning attitudes ($F = 0.369$, $p = 0.546 > 0.05$). While both groups improved, the difference in attitude gains between the experimental group and the control group was not significant. Therefore, further analysis was conducted on individual attitude subscales to explore the effects of different instructional media on specific dimensions of learning attitudes.

Table 9. ANCOVA results on mathematics learning attitudes for both groups.

Source	Type III Sum of Squares	df	F	p	Eta squared
Pre-test	6009.498	1	93.493	0.000	6009.498
Group	23.734	1	0.369	0.546	23.734
Error	3663.836	57			
Total	223340.000	60			

To further investigate group differences, mathematics learning attitudes were analyzed across five subscales: Practicality, Confidence, Motivation, Strategy Use, and Help-Seeking. Table 10 presents the paired-sample t-test results for the experimental group. The results showed notable improvements in the subscales of Practicality (mean difference = 0.39, $p = 0.011$), Confidence (mean difference = 1.08, $p < 0.001$), Strategy Use (mean difference = 0.44, $p < 0.01$), and the Overall Score (mean difference = 0.31, $p = 0.003$). Among these results, the greatest improvement was in the Confidence dimension, indicating that the interactive virtual robotic system significantly enhanced students' self-confidence in learning spatial vector concepts.

Table 10. Paired-samples t-test results for the experimental group's mathematics learning attitudes.

Orientation	Pre-test		Post-test		p
	Mean	SD	Mean	SD	
Practicality	3.36	0.700	3.75	0.856	0.011*
Confidence	1.70	0.753	2.78	1.073	0.000***
Motivation	4.20	0.640	4.34	0.577	0.252
Strategy Use	2.94	0.793	3.38	0.946	0.001**
Seeking Support	3.82	0.815	3.87	0.629	0.743
Overall	3.27	0.551	3.58	0.721	0.003**

*p < 0.05, **p < 0.01, ***p < 0.001.

Table 11 presents the paired-sample t-test results for the control group across the five attitude subscales. Significant improvements were observed in Practicality (mean difference = 0.65), Confidence (mean difference = 1.02), and the Overall Score (mean difference = 0.43). Among these, the most substantial gains occurred in the Practicality and Confidence dimensions, indicating that even with traditional interactive materials, students' recognition of mathematics' practicality and their confidence in learning improved positively following the instructional intervention.

Table 11. Paired-samples t-test results for the control group's mathematics learning attitudes.

Orientation	Pre-test		Post-test		p
	Mean	SD	Mean	SD	
Practicality	2.89	0.544	3.54	0.748	0.000***
Confidence	2.43	0.777	3.45	0.963	0.000***
Motivation	3.29	0.829	3.36	0.821	0.517
Strategy Use	3.18	0.962	3.33	0.893	0.080
Seeking Support	3.56	0.936	3.51	0.845	0.736
Overall	3.22	0.776	3.45	0.144	0.005**

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

To further examine differences in the magnitude of improvement between groups, an ANCOVA was conducted on each attitude subscale. Prior to the analysis, the homogeneity of regression slopes was tested. Only the Practicality and Strategy Use subscales met this assumption, with non-significant interaction effects ($p = 0.557$ and $p = 0.681$, respectively). Subsequent ANCOVA results (Table 12) revealed a significant group effect on the Practicality subscale ($p = 0.012 < 0.05$). This indicates that students in the experimental group, using the virtual robotic system, demonstrated a significantly greater improvement in recognizing the practicality of mathematics compared to the control group. This suggests that the experimental group was more likely to view mathematics as a valuable tool for developing logical thinking and addressing real-life problems.

Table 12. ANCOVA results on the practicality of mathematics learning attitudes for both groups.

Source	Type III Sum of Squares	df	F	p	Eta squared
Pre-test	106.425	1	38.784	< 0.001	0.405
Group	18.260	1	6.654	0.012*	0.105
Error	156.409	57			
Total	8399.000	60			

*$p < 0.05$.

4.3. Analysis of Cognitive Load

This section summarizes the differences in perceived cognitive load between the experimental and control groups after completing the instructional intervention. The cognitive load questionnaire used in this study consisted of 7 items covering two dimensions: mental load and mental effort. A 5-point Likert scale was used, with higher scores indicating greater cognitive load—that is, more cognitive effort required during the learning process. According to the results in Table 13, the average cognitive load score of the experimental group was 3.35, while the control group was 3.15. Although the experimental group reported slightly higher cognitive load, the difference was not statistically significant ($p = 0.408 > 0.05$). This suggests that although using the virtual robotic system in mathematics instruction may increase cognitive demands, its inclusion did not lead to a significant difference in students' cognitive load compared to traditional instructional methods, indicating the system's usability and effective design.

Table 13. Results of the independent-samples t-test comparing cognitive load between both groups.

Group	Mean	SD	df	t	p
Experimental Group	3.35	6.050	58	0.834	0.408
Control Group	3.15	7.209			

Mental load refers to the cognitive demands imposed by the nature of the learning task or environment, while mental effort reflects the amount of cognitive resources and effort a learner actively invests during task execution. According to the results in Table 14, the experimental group reported higher mean scores than the control group in both dimensions. However, the differences between the two groups were not statistically significant. These findings suggest that while integrating a virtual robotic system may enhance learners' cognitive engagement, it does not lead to a statistically significant increase in mental load or mental effort.

Table 14. Comparison of mental load and mental effort between the two groups.

Group	Mental Load			Mental Effort		
	Mean	SD	p	Mean	SD	p
Experimental Group	3.50	3.553	0.198	3.16	2.713	0.861
Control Group	3.18	4.154		3.11	3.155	

Table 15 presents the item-level statistics from the cognitive load questionnaire for both groups. Overall, the experimental group reported slightly higher scores than the control group across most items. Notably, for Item 1—"The learning content in this activity was difficult for me"—the difference reached statistical significance ($p = 0.044 < 0.05$). This suggests that learners in the experimental group perceived the learning content as more difficult than those in the control group. One possible explanation is that, within the same instructional time, students in the experimental group were required not only to learn the same mathematical content as the control group but also to manipulate the virtual robotic arm while completing the learning tasks. As a result, they faced greater time pressure and operational demands, requiring more cognitive resources to complete the tasks, which may have contributed to the increased perception of cognitive load.

In summary, although the integration of a virtual robotic arm into the interactive learning system may have increased task complexity and operational demands in specific contexts, it did not lead to a significant increase in overall cognitive load. These findings provide important insight for interpreting learners' system satisfaction and instructional effectiveness in subsequent analyses.

Table 15. Statistics on the scores of the two groups in each of the questions on cognitive load.

Source	Subject	Experimental Group		Control group		p
		Mean	SD	Mean	SD	
Mental Load	1. The learning content in this activity is difficult for me.	3.87	1.042	3.30	1.088	0.044*
	2. It takes me a great deal of effort to answer the questions in the learning activity.	3.43	0.898	3.17	1.147	0.320

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	3. Learning the content of this activity is confusing and frustrating.	3.40	1.003	3.17	1.020	0.375
	4. I do not have enough time to learn the content of this activity.	3.30	1.119	3.07	1.143	0.427
Overall mental load Mean and Standard Deviation		3.50	0.888	3.18	1.038	0.198
Mental Effort	5. In this learning activity, the way of teaching or the way of presenting the contents of the teaching materials is more difficult for me.	3.23	1.073	3.17	1.020	0.806
	6. I have to put a lot of effort into completing this learning activity or achieving its goals.	3.23	1.073	3.17	1.177	0.819
	7. The learning activity is taught in a way that is difficult to understand or follow.	3.00	1.050	3.00	1.203	1.000
Overall Mental Effort Mean and Standard Deviation		3.16	0.904	3.11	1.052	0.861
Overall Cognitive Load Mean and Standard Deviation		3.35	0.864	3.15	1.030	0.408

*$p < 0.05$.

4.4. Analysis of System Satisfaction

This section analyzes differences in system satisfaction between the experimental and control groups after using the spatial vector interactive learning system. The system satisfaction questionnaire consisted of 7 items across two dimensions: perceived usefulness and perceived ease of use. A 5-point Likert scale was used, with higher scores indicating greater satisfaction with the system.

According to the independent-samples t-test results shown in Table 16, the experimental group reported a higher mean satisfaction score (Mean = 3.88) compared to the control group (Mean = 3.39). The difference was statistically significant ($p = 0.038 < 0.05$), indicating that students who used the interactive virtual robotic system were significantly more satisfied than those who used the traditional teaching materials. Overall, the students who engaged with the system incorporating the virtual robotic arm expressed higher satisfaction, with the difference reaching statistical significance. To further explore the underlying factors influencing satisfaction, the following sections present detailed analyses of the two subscales: perceived usefulness and perceived ease of use.

Table 16. Results of the t-test on the satisfaction level of both groups of systems.

Group	Mean	SD	df	t	p
Experimental group	3.88	5.812	58	2.124	0.038*
Control group	3.39	6.681			

*$p < 0.05$.

The system satisfaction questionnaire used in this study included two dimensions: perceived usefulness and perceived ease of use. Perceived usefulness refers to the extent to which learners believe the system positively contributes to their learning, while perceived ease of use reflects how simple and user-friendly the system is to operate. According to the results presented in Table 17, the experimental group reported a significantly higher mean score (Mean = 3.99) in perceived usefulness compared to the control group (Mean = 3.38), with the difference reaching statistical significance ($p = 0.011 < 0.05$). This suggests that learners found the virtual robot-based interactive system to be more beneficial for enhancing their understanding and learning outcomes than the standard interactive materials. In terms of perceived ease of use, the experimental group also reported a higher mean score (Mean = 3.82) than the control group (Mean = 3.38), though the difference was not statistically significant ($p = 0.198 > 0.05$). These findings indicate that despite the added complexity of operating the virtual robot, learners did not perceive the system as difficult to use and considered it to maintain a satisfactory level of usability.

Table 17. Comparison of Perceived Usefulness and Perceived Ease of Use between the two groups.

Group	Perceived usefulness				Perceived ease of use			
	Mean	SD	t	p	Mean	SD	t	p
Experimental Group	3.99	3.459	2.613	0.011*	3.72	2.805	1.303	0.198
Control Group	3.38	3.748			3.38	3.130		

*p < 0.05.

Table 18 presents item-level statistics for system satisfaction scores between the experimental and control groups. In the perceived usefulness dimension, all items showed higher mean scores for the experimental group. The most notable difference was found in Item 4. The interactive materials helped me learn better which reached a statistically significant level (p = 0.006**). This result indicates strong agreement among students in the experimental group that the virtual robot-integrated system significantly enhanced their learning effectiveness. In the perceived ease of use dimension, only Item 7 "Overall, the interactive system used in this activity was helpful and easy to use" showed a statistically significant difference (p = 0.015*). Although the overall ease-of-use ratings did not significantly differ across most items, this result suggests that learners generally viewed the system as supportive of their learning and user-friendly, with the virtual robot integration not posing a substantial usability barrier.

Table 18. Statistical results of the two groups on each question of system satisfaction.

Source	Subject	Experimental Group		Control Group		p
		Mean	SD	Mean	SD	
Perceived Usefulness	1. Learning through the interactive materials enriches the learning activities.	3.97	0.850	3.37	1.129	0.024*
	2. Learning through the interactive teaching materials is helpful for me to learn new knowledge.	3.97	0.928	3.40	1.003	0.027*
	3. The learning mechanism provided by the interactive teaching materials makes the learning process smoother.	3.93	1.015	3.37	0.999	0.033*
	4. Interactive teaching materials can help me learn better.	4.10	0.923	3.40	0.968	0.006**
Overall Perceived Usefulness Mean and SD		3.99	0.864	3.38	0.937	0.011*
Perceived Ease of Use	5. It only took me a short time to learn how to use the interactive teaching material.	3.47	1.224	3.30	1.055	0.574
	6. I found the interface of the interactive materials easy to use.	3.63	1.033	3.43	1.165	0.485

	7. Overall, the teaching materials used in this learning activity are helpful and easy to use.	4.07	0.868	3.43	1.073	0.015*
Overall Perceived Ease of Use Mean and SD		3.72	0.935	3.38	1.043	0.198
Overall System Satisfaction Mean and SD		3.88	0.830	3.38	0.954	0.038*

*$p < 0.05$, **$p < 0.01$.

5. Discussion

This section presents a summary of the data analysis, building on the previous findings. It specifically addresses the research questions of this study in relation to learning outcomes, attitudes toward mathematics learning, and cognitive load.

5.1. System Development and Satisfaction

The virtual robotic system developed in this study was designed using the ADDIE instructional model and implemented with VR technology through the Unity 3D game engine. It provides interactive learning experiences by employing a virtual robotic arm to generate 3D visualizations of spatial coordinate transformations, thereby enhancing the comprehension and concretization of abstract spatial vector concepts.

To support learning, the system incorporates real-time feedback and contextual prompts, enabling learners to clarify and consolidate mathematical concepts throughout the learning process. Based on the system satisfaction survey, learners in the experimental group reported significantly higher perceived usefulness compared to the control group. Although there was no significant difference in perceived ease of use, both groups expressed positive feedback, indicating that the integration of the virtual robotic system did not hinder usability. Overall, students perceived the system as effective in enhancing their understanding of spatial vectors. Its interactive design enriched the learning content, improved conceptual clarity, and fostered greater learning motivation.

5.2. Assessment of Student Learning

Based on the research objectives, this study analyzed and discussed the statistical results regarding learning achievement, mathematics learning attitudes, and cognitive load of students in both the experimental and control groups following the spatial vector instructional intervention. The main findings are summarized as follows:

- Learning Achievement

Both groups demonstrated significant improvement following the instructional intervention; however, the experimental group utilizing the virtual robotic system achieved greater progress. These results suggest that integrating a virtual robot into instruction can effectively enhance students' understanding of spatial vector concepts..

- Mathematics Learning Attitudes

Overall attitudes improved in both groups, particularly in the dimensions of perceived usefulness and confidence toward learning mathematics. Although the difference in total attitude scores between groups was not statistically significant, the experimental group demonstrated notably higher perceptions of usefulness.

- Cognitive Load

While the experimental group reported slightly higher average scores in overall cognitive load, mental load, and mental effort, no significant differences were found between the two groups. Some individual items (e.g., perceived task difficulty) did show significant differences, possibly due to the increased complexity and time required for robot operations. Nonetheless, the cognitive load remained within an acceptable range.

In summary, the integration of a virtual robotic system demonstrated positive effects in enhancing student achievement in learning spatial vector concepts, supporting favorable learning attitudes, and maintaining manageable cognitive demands. These findings offer empirical support for the future development and application of immersive and interactive learning technologies in mathematics education.

6. Future Work

This section presents suggestions to enhance the virtual robotic system, optimize instruction, and refine research variables. Future efforts will expand learning content, improve engagement, extend instructional time, assess long-term outcomes, and address individual differences to better support diverse learners and learning effectiveness.

6.1. Suggestions for System Design

The virtual robotic system developed in this study effectively enabled learners to visualize abstract spatial vector concepts through immersive 3D visualizations and interactive, hands-on manipulation. However, the current instructional content is confined to fundamental concepts and lacks comprehensive coverage of advanced vector applications. Future development should aim to broaden the instructional scope by incorporating more advanced topics in spatial vector mathematics, thereby enhancing the system's comprehensiveness and educational impact. Additionally, while learners generally perceived the system as helpful for understanding, feedback indicated that improvements in interactivity and engagement are still needed. To increase learning motivation, future versions may incorporate gamified elements, scenario-based learning, and improved user interface design to simplify operation and reduce cognitive load. These enhancements could contribute to better learning outcomes and user satisfaction.

6.2. Suggestions for Experimental Design

The total instructional time for this study was 100 minutes, including teaching activities, assessments, and questionnaires. This limited time frame may have imposed cognitive pressure on students, potentially affecting performance. It is recommended that future implementations consider extending instructional time or simplifying user interface to reduce cognitive load and deepen learning engagement.

Moreover, post-tests were administered immediately after the intervention, primarily measuring short-term learning outcomes. To evaluate long-term retention, future studies should consider follow-up assessments or delayed post-tests. This would help determine whether learners can internalize and transfer spatial vector concepts over time, offering a more comprehensive understanding of the system's sustained impact.

6..3. Suggestions for Research Variables

This study primarily compared group-level outcomes and did not account for individual differences in prior achievement. In real classroom settings, variations in students' academic performance are inevitable. Future research is encouraged to categorize participants by achievement level (e.g., high, medium, low) and conduct subgroup analyses. This could provide deeper insight into how the system supports learners with different ability levels and inform the development of personalized instructional strategies.

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