

Mathematical conceptual analysis of two linear algebra-based learning games

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Article Info

Article history:

Received 11 17, 2025
Accepted 12 18, 2025
Published 06 01, 2026

Keywords:

Linear Algebra
Interactive media
Matrix transformation
Linear combinations
Applied mathematics.

ABSTRACT

This study aims to analyse mathematical representations in two interactive media: vector unknown and GeoGebra-based linear transformation simulation, within the context of applied linear algebra learning. Using a qualitative-descriptive approach, this study examines the consistency of symbolic structure, spatial visualisation, and applicative relevance across the two media. The results of the analysis show that *Vector Unknown* is effective at representing a combination of linear and result spaces, whereas GeoGebra excels at visualising matrix and determinant transformations. Both support conceptual understanding and modelling skills that are essential in the fields of Engineering, computer graphics, and spatial systems. The study confirms that interactive media can bridge the gap between abstraction and real-world applications, encouraging inquiry-based learning. The limitations of this study include the limited scope of the concept and the absence of empirical validation based on user performance. Therefore, further research is recommended to expand the media and the scope of concepts.

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1. INTRODUCTION

The development of digital technology over the past two decades has had a profound impact on education, particularly in mathematics learning. The integration of technology and learning has given rise to various interactive media innovations, one of which is *educational games* that not only serve as entertainment but also provide a visual means for understanding abstract ideas [1]. Game-based approaches and interactive simulations have been shown to

increase motivation to learn, deepen cognitive engagement, and strengthen students' conceptual thinking skills.

In the context of advanced mathematics learning, such as linear algebra, students often face difficulties in understanding abstract concepts, including linear combinations, vector spaces, linear transformations, and matrix operations, which are not only symbolic but also require strong visual representation skills to be understood intuitively. Many students can manipulate algebraic procedures but struggle to relate them to their underlying geometric meaning, which limits their conceptual understanding [2]. Therefore, visual and interactive media, such as educational games, dynamic simulations, and algebra-based software, are emerging as effective alternatives that bridge the gap between mathematical symbols and visual interpretation, thereby increasing learning engagement and strengthening in-depth understanding of concepts.

Several studies have shown that game-based learning in mathematics can enhance students' conceptual understanding and critical thinking [3]. However, most research focuses on pedagogical aspects and on improving learning outcomes rather than on mathematical analysis of the media's internal structure. In fact, game-based media can be studied as a mathematical system that represents a formal model of the theory being taught. In this case, a conceptual analysis of *games* and linear-algebra-based simulations can provide new insights into how mathematical concepts are translated into interactive mechanisms.

Linear algebra is a fundamental branch of mathematics, widely used across disciplines such as physics, engineering, economics, and computer science [4]. Concepts such as linear combinations, result spaces, and linear transformations underlie many modern computing applications. However, its abstract nature often makes it difficult for students to understand the relationship between symbolic and visual representations. Therefore, an exploration-based approach and visual manipulation are practical learning strategies [5]. Interactive media allows students to "see" the effects of linear transformations directly and understand the relationship between mathematical theory and geometric representations.

One interactive learning medium that supports understanding of linear algebra concepts is *Vector Unknown*, a web-based educational game developed by the Inquiry-Oriented Linear Algebra (IOLA) team at North Carolina State University [6]. In this game, players are given two basic vectors \vec{u} and \vec{v} , and are asked to determine the scalars a and b so that the linear combination $\vec{r} = a\vec{u} + b\vec{v}$ exactly achieves the target position provided. Through the interactive interface, players can adjust the value and view the position in real time. Coordinate fields are available in real time, enabling intuitive visualisation of the output space (SPAN) and linear dependencies. This visual-dynamic mechanism helps students connect symbolic representations with relevant geometric images. Mauntel, Wawro, and Rasmussen's research shows that *Vector Unknown* is effective in strengthening students' understanding of the relationship between mathematical forms and visual interpretation in linear algebra [2]. This game is available for free at the address provided in reference [7].

In addition to *Vector Unknown*, the GeoGebra software also plays a vital role as a linear algebra exploration tool. Although GeoGebra is not a formal educational game, its use in learning contexts can be characterised as a game-like simulation, as it features interactivity, variable manipulation, and visual feedback that resemble those of educational games [8]. In the linear transformation module, the user can manipulate matrix elements

$$A = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$$

and observe the results of the transformation $T(\vec{x}) = A\vec{x}$ directly on the coordinate field. In this activity, an intuitive understanding of determinants and *eigenvectors*, as well as the influence of changes in matrix parameters on geometric shapes, is encouraged [9]. This simulation is available free of charge at [10]. Thus, the *GeoGebra-based simulation* in this study is positioned as an interactive medium that supports conceptual analysis of linear algebra with an exploratory approach.

This study does not assess the empirical effectiveness of learning. Still, it focuses on a mathematical conceptual analysis of how the concepts of linear combination and linear transformation are represented in the mechanism of the two interactive media. Through this approach, a deeper understanding of the relationships among game structure, mathematical functions, and linear algebraic concepts will be achieved. This analysis also provides a theoretical basis for developing more meaningful and mathematically accurate digital learning media for mathematics.

2. METHOD

This study employs a qualitative-descriptive approach, focusing on the mathematical conceptual analysis of two interactive learning media: *Vector Unknown* and a *GeoGebra-based linear transformation simulation*. This approach was chosen because the research is not oriented toward empirical measurement of learning effectiveness, but rather toward an in-depth description and elaboration of how the main concepts of linear algebra are represented through game mechanics and visual simulations. Analysis of the mathematical structure of digital media is essential in modern mathematics education research, as visual and interactive representations are key components in developing students' conceptual understanding. Therefore, this research methodology is designed to explore the relationship between linear algebra theory and its implementation on two interactive platforms that serve as the study objects [11].

The research object consists of two open-access digital media. The first medium, *Vector Unknown*, is a web-based game developed by the Inquiry-Oriented Linear Algebra (IOLA) team to explore linear combinations. *This game* is a medium for exploring linear combinations. *This game* has an explicit mathematical structure, as evident in the model.

$$r = \overline{a}u + \overline{b}v,$$

Through this feature, users can manipulate scalar values, a and b , to generate target vectors. The second medium is a *GeoGebra-based linear transformation simulation* that enables users to modify matrix elements and observe geometric changes in real time as the model evolves.

$$T(\vec{x}) = A\vec{x}.$$

These two media were chosen because they represent two distinct forms of interactivity in linear algebra learning: linear combination manipulation and matrix transformation manipulation.

The research data were analysed with respect to game structure, visual interface, mathematical representation, transformation algorithm, visual response to parameter changes, and supporting documentation from previous research on these two media. The analysis was carried out in three stages. The first stage involves identifying mathematical concepts that appear within the medium, such as two-dimensional vectors, linear combinations, result spaces (or spans), linear dependencies, linear transformations, transformation matrices, determinants, rotations, dilations, reflections, and friction. At this stage, the emerging mathematical structure is compared with formal definitions in the linear algebra literature to ensure the accuracy of the concept's representation [12].

The second stage involves analysing visual and symbolic representations. This analysis explores how linear algebra concepts are translated into graphical visualisations, including vector orientation, changes in object position, geometric shape deformations, and the relationship between input-value manipulation and visual changes. This analysis follows a mathematical-visualisation research framework that elucidates the critical role of visual representation in understanding abstract concepts [13].

The third stage involves validating the concept through theoretical triangulation. The results of the analysis were compared with the formal literature on linear algebra, a calm study of linear algebra learning, and previous studies on the use of interactive media in mathematics education. This validation is essential to ensure that the interpretation is not based solely on visual observation but is consistent with established mathematical theories [14].

After a comparative analysis of the two methods, the following criteria were considered: the accuracy of mathematical expressions, the depth of the concepts presented, the consistency between symbolic and visual representations, the flexibility of parameter manipulation, and the quality of the geometry. This criterion refers to the standard for analyzing mathematical visual media used in contemporary research on mathematics education technology [15]. Through this analysis, the study aims to demonstrate how the two media effectively convey the concepts of linear combination and linear transformation and how they can complement each other in inquiry-based mathematical learning.

3. RESULTS AND DISCUSSION

An analysis of two interactive media, namely Vector Unknown and GeoGebra-Based Learning, reveals that linear algebra concepts can be effectively represented visually through game mechanics and geometric transformations. Visual representations like this have been shown to strengthen students' understanding of mathematical structures by supporting the connection between symbolic and geometric representations of linear concepts [11].

3.1. Representation of Linear Combinations in *Vector Unknown*

The *vector unknown game* illustrates the basic concept of linear algebra: forming new points by combining two basic vectors. Suppose the two vectors given are vectors. An unknown *game* implements a basic idea of linear algebra: forming new points by linearly combining two basic vectors.

Suppose the two vectors given are,

$$\vec{u} = (u_1, u_2) \quad \vec{v} = (v_1, v_2)$$

The *game* uses only the core formula:

$$\vec{r} = a\vec{u} + b\vec{v}$$

To show how the formula generates new coordinates, the following algebraic decomposition is performed [12]:

$$a\vec{u} = a(u_1, u_2) = (au_1, au_2),$$

$$b\vec{v} = b(v_1, v_2) = (bv_1, bv_2).$$

Since vector summing is done on a component-by-component basis, then:

$$\vec{r} = (au_1 + bv_1, au_2 + bv_2).$$

This derivative shows that changes in values and within the game affect the coordinates of the result linearly. When the player slides the slider or presses the scalar value key, *the vector unknown* updates the point's position using this derived formula, without displaying the matrix form of the entire calculation, which is expressed in coordinate terms.

Furthermore, the concept of derivatives also clarifies the relationship between the structure of a vector space and the mechanics of the game. If the determinant of a vector pair (\vec{u}, \vec{v}) is not the same as zero (meaning that both are not collinear), then a linear combination can produce all points on the plane. On the other hand, if the vector is collinear, then the output space (span) only forms one straight line, so the player will not be able to reach the points that are outside that line. This is explicitly visualised in the game when the target is out of range of possible linear combinations. Mathematically, if two basic vectors \vec{u} and \vec{v} are collinear (i.e., one is a scalar multiple of the other), then the resulting space of the linear combination forms only one straight line, which is referred to as the span of the two vectors:

$$\text{span}(\vec{u}, \vec{v}) = \{a\vec{u} + b\vec{v}\}$$

It is only a single line. This condition is very evident in the game when the target is outside the line.

3.2. Linear Transformation Derivatives in *GeoGebra-Based Learning*

In GeoGebra media, linear transformations are represented by a general equation:

$$T(\vec{x}) = A\vec{x}, \quad A = \begin{bmatrix} a & b \\ c & d \end{bmatrix}.$$

With vectors, input:

$$\vec{x} = (x_1, x_2),$$

The transformation is derived as follows:

$$A\vec{x} = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}.$$

The transformation is derived as follows:

$$\begin{bmatrix} ax_1 & + & bx_2 \\ cx_1 & + & dx_2 \end{bmatrix}.$$

GeoGebra uses the result of this matrix-vector multiplication to move each point on the plane. Every small change to a matrix element via the slider is directly reflected in the geometric object, allowing students to observe the effects of linear transformations in real time.

To show the change in the area of the wake after the transformation, GeoGebra uses the properties of the determinants:

$$\det(A) = ad - bc.$$

The theory establishes the broad relationship that linear transformations change the wake-up time the day after by the determinant factors:

$$\text{New area} = |\det(A)| \cdot \text{Original area}.$$

This formula is not added from the outside, but is a direct property of the definition of a 2D linear transformation. When the determinant is positive, the wake orientation is maintained; if negative, the build collapses; if zero, the build collapses to a line or a point [16].

This visual interaction helps students understand that determinants are not merely abstract numbers but have direct geometric meanings. In addition to changes in the building's position and area, linear transformations preserve the vector structure. GeoGebra allows students to observe that the properties of linearity remain valid, namely:

$$T(a\vec{x} + b\vec{y}) = aT(\vec{x}) + bT(\vec{y})$$

This property shows that linear transformations not only move points, but also maintain linear relationships between vectors. This is important for understanding the vector space structure and linear functions as consistent mappings of vector operations.

The concept of bases and dimensions can also be explored through this medium. In *Vector Unknown*, two non-collinear base vectors form the basis for \mathbb{R}^2 , all points on the plane can be achieved through linear combinations. This reinforces the understanding that the dimensions of a vector space are determined by the number of free vectors in its basis. [12].

GeoGebra also allows exploration of the inverse transformation: when matrix A has an A^{-1} , the equation $Ax = b$ becomes $x = A^{-1}b$, and the transformation can be reversed. Students can test this condition by changing the matrix elements and observing whether the geometric shape returns to its original position. This concept is essential in solving linear systems and modelling dynamic systems [17].

3.3. Consistency between Algebraic Models and Game Visualisation

The analysis reveals that the mathematical derivatives employed in the games *Vector Unknown* and *GeoGebra-Based Simulation* are consistent with the fundamental principles of linear algebra. In *Vector Unknown*, players intuitively learn how linear combinations work by observing point displacements on the coordinate field, which directly represents the structure of the resulting space and the linear dependencies between vectors. This representation helps students understand that changes in scalar values affect the position of the result vector, and that achieving the target depends on the linear independence of the base vectors. This mechanism not only deepens understanding of linear combinations but also provides an in-depth exploration of two-dimensional vector spaces.

Meanwhile, *the GeoGebra-based simulation* enhances students' understanding of linear transformations by allowing them to manipulate matrix elements and directly observe geometric transformations. Visualisations of area deformation, rotation, reflection, and dilation resulting from changes in matrix parameters provide a concrete picture of the determinant's effects and the wake's orientation. This interactivity enables students to consistently connect symbolic expressions with spatial representations. This understanding aligns with the modern linear algebra literature, which emphasises the importance of integrating symbolic algebra and geometric visualisation in the learning of linear concepts, as well as supporting the transition from applied to conceptual understanding in applied mathematics [17].

3.4. Applied Relevance and Conceptual Synthesis

The consistency between mathematical and visual models supports conceptual understanding and demonstrates potential applications across fields that utilise linear algebra as a foundation. In applied mathematics, linear combination representations and matrix transformations have direct implications for modelling physical systems, computer graphics, spatial data analysis, and control techniques [9].

For example, the linear combination model in *Vector Unknown* can be associated with a two-dimensional navigation system that determines an object's final position based on the directional weights of the base vectors. This approach is used in position-interpolation algorithms, robotic motion, and trajectory simulations in graphics programming [2]. This reflects the basic principles in Cartesian coordinate systems and linear mapping, which are widely used in software engineering and automation systems.

Meanwhile, the linear transformation in *GeoGebra* is fundamental to image processing and spatial transformation. Changes in matrix elements directly affect the orientation and shape of objects, which are standard techniques in image rotation, shape reflection, and deformation analysis in the fields of Civil Engineering, architecture, and CAD (Computer-Aided Design) [9]. Thus, this media is not only educational, but also reflects the geometric transformation process used in professional practice.

3.5. Pedagogical Implications in Applied Mathematics Learning

Both media make a significant contribution to exploratory and inquiry-based learning approaches, which are highly relevant in STEM Education. By allowing students to manipulate parameters and observe their impact firsthand, these media encourage active engagement and the development of spatial intuition and mathematical modelling skills.

Mauntel and Zaindeh's research demonstrates that the use of game-based media and simulation can help students construct spatial structures and gain a deeper understanding of the relationships among concepts in linear algebra [18]. This supports the transition from a procedural understanding to a more applicative conceptual knowledge, which is especially important in the context of Engineering Education and applied science.

3.6. Validation through Theoretical Triangulation

To ensure that the conceptual interpretation in this analysis is not merely observational zero, validation is also achieved through theoretical triangulation, as described in the methodology. This validation includes comparing the study results with three main categories of sources. First, the formal literature on linear algebra, such as Strang [12], is used as a reference to assess the accuracy of mathematical expressions, vector space structures, and properties of linear transformations. Second, research on linear algebra learning, including the study of Mauntel et al. [18] and Turgut [9], provides an empirical and pedagogical context for the use of interactive media in understanding the concept of LIEAR. Third, the study of visualisation and interactive media in mathematics education, as discussed by Murphy [11] and Ziatdinov and Valles [17], emphasises integrating symbolic and visual representations in STEM education.

Through this triangulation, it was found that the representation of linear combinations in *Vector Unknown* and of matrix transformations in *GeoGebra* not only aligns with formal definitions but also supports pedagogical principles grounded in exploration and visualisation. For example, the use of determinants in *GeoGebra* to show changes in the wake area is consistent with the theory of two-dimensional linear transformations [12]. Similarly, the representation of the result space in *Vector Unknown* explicitly reflects the concepts of span and linear dependence as described in modern linear algebra. Thus, this triangulation reinforces the conceptual validity of the analysis results, showing that both media are not only visually intuitive but also mathematically and pedagogically relevant.

3.7. Synthesis of Media Comparison

Based on the analysis, here is a comparison of the characteristics of the two media in the context of applied mathematics:

Table 1. Comparison of the Characteristics of the Two Media in the Context of Applied Mathematics

Analysis Aspect	<i>Vector Unknown</i>	<i>Geogebra-Based Simulation</i>
Concept Focus	Linear Combinations	Linear Transformation
Mathematical Representation	Scalar dan Vector	Matrix and Vector

Interactivity	Discrete, target-based	Continuous, exploration-based
Visualization	Position of the point of the combination result	Deformation of geometric shapes
Applied Relevance	Navigation, trajectory, interpolation	Image processing, spatial transformation
Implementable Contribution	Understanding of the result space and dependencies	Understanding determinants and orientation

Source: Synthesized from [2], [8], and [16].

The combination of these two media can enrich linear algebra learning in an applied context, particularly in educational software development, Engineering simulation training, and project-based teaching. In addition, this approach can serve as a strong conceptual basis for developing more complex, context-sensitive digital learning media, such as eigenvector-based simulations, linear dynamic systems, or transformations in high-dimensional spaces.

4. CONCLUSION

This study demonstrates that the interactive media Vector Unknown and the GeoGebra-based Linear Transformation Simulation can visually and manipulatively represent the fundamental concepts of linear algebra and align with formal mathematical structures. The main findings indicate that both media support spatial and symbolic understanding of linear combinations, matrix transformations, and determinants, and are directly relevant to applied mathematics.

This research is necessary because it bridges the gap between the abstract representations of linear algebra and their applications in digital systems, including spatial navigation, image processing, and geometric design. Using a descriptive qualitative approach, this study successfully addresses the main objective of identifying the contribution of interactive media to understanding and applying linear algebra concepts in an applied context, as formulated in the introduction.

However, this study has some limitations. First, the analysis covers only two media and does not address advanced concepts such as eigenvectors or linear dynamic systems. Second, validation is conducted conceptually, without empirical tests of user performance on real-world application tasks. Third, the descriptive approach has not been supported by longitudinal data capable of measuring the long-term impact on students' applicative competence.

For further research, it is recommended that interactive media be further developed by incorporating advanced features and tested in real-world problem-solving contexts, such as robotic simulation or spatial mapping. Interdisciplinary collaboration between applied mathematicians, educational software developers, and STEM educators also needs to be strengthened to produce mathematically accurate and technically relevant media.

Thus, this study makes an essential contribution to the development of linear algebra-based learning media that not only support conceptual understanding but also strengthen applicative competencies in applied mathematics education.

ACKNOWLEDGEMENTS

We would like to thank the media developers Vector Unknown and GeoGebra for their contributions in providing innovative mathematical exploration tools. We also express our appreciation to the supervisors, colleagues, and all parties who have provided support, conceptual input, and facilities throughout the preparation of this article. Constructive collaboration and discussion play a key role in enriching the analysis and strengthening the quality of our research.

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