Enhancing Mathematics Education with Geometrix: A Study on the Effectiveness of Gamified 2D and 3D Animation Tools

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Abstract. *This paper presents a comprehensive study on integrating computer graphics and virtual reality into the teaching of geometry, with a focus on complex visualization concepts. The authors developed Geometrix, an interactive software leveraging React and WebGL, to create a gamified learning environment to increase student motivation and understanding of mathematical topics. A pilot study involving high school students demonstrated significant improvements in test scores and student preference for the software over traditional teaching methods. The study highlights the potential of visualization tools and gamification techniques in transforming mathematics education, making it more engaging and accessible for students.*

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1. Introduction

Contemporary mathematics education is confronted with the significant challenge of students struggling to comprehend abstract concepts, often leading to a lack of engagement. In response to these challenges, this paper explores the transformative potential of visualization tools in the teaching of mathematics. We discuss the advantages and challenges of incorporating these tools into the classroom, drawing from a review of literature, case studies, and best practices to provide a holistic understanding of their impact.

In the presented context, the approach proposed in this study is based on the proprietary software Geometrix, with the challenges of keeping students engaged with learning while solving proposed problems and explaining mathematical concepts through 2D visualization and animations. By utilizing animation tools and gamification aspects, Geometrix aims to address the described challenges and positively impact education (Figure 1).

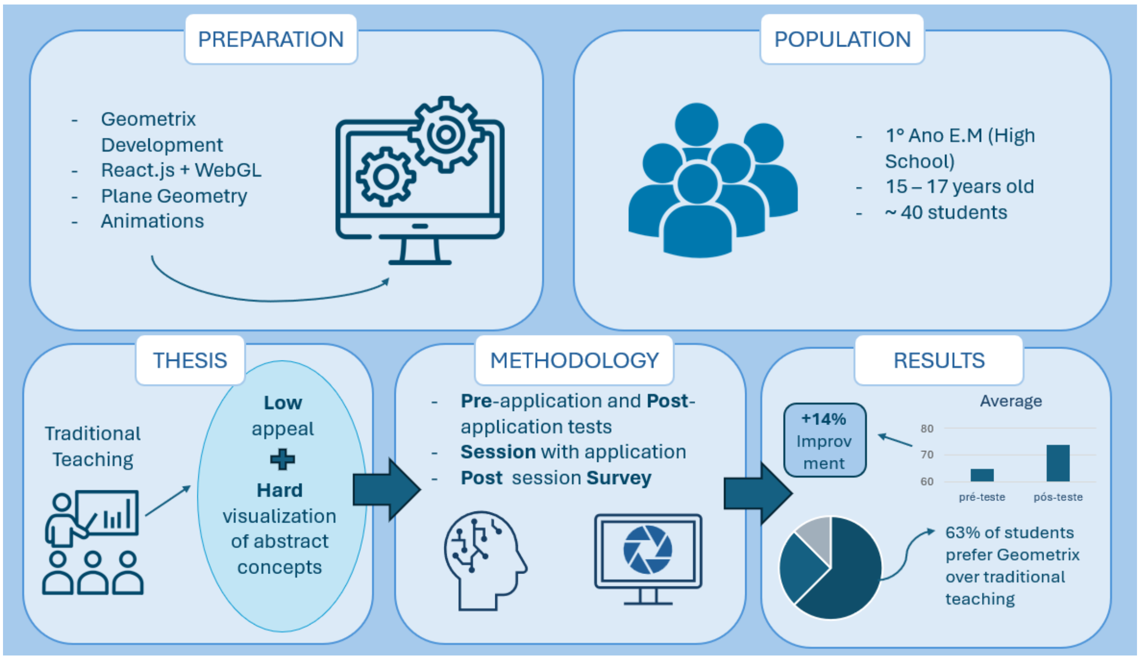

Figure 1. Paper Abstract (numerical results are illustrative).

Visualization tools, encompassing graphic software, interactive animations, and simulators, offer a promising approach to making learning mathematics more accessible and stimulating. These tools have been shown to facilitate the understanding of complex mathematical concepts and to foster student curiosity and active learning. For instance, research indicates that spatial skills can be enhanced through targeted training, leading to improved performance in mathematics [Tom Lowrie 2018]. Similarly, the implementation of 3D-based methodologies has been associated with increased student grades and reduced failure rates [Luis Medina Herrera 2019].

The evolution of digital technologies has expanded the possibilities and impacts of mathematical visualization, which is fundamental for constructing mental images that are crucial for understanding and solving mathematical problems [Arcavi 2003]. Innovative applications such as augmented reality and 3D printing have demonstrated considerable advancements in students' comprehension of complex concepts and their practical application [Juan Martín-Gutiérrez 2015].

This paper argues that the integration of visualization tools and 3D methodologies not only makes learning more engaging but also allows for personalized teaching, addressing the diverse needs and learning styles of students. Tools like GeoGebra and Desmos enable dynamic exploration of mathematical concepts, providing a more interactive and engaging learning experience. The literature suggests that students' intrinsic motivation, combined with the development of spatial skills, is pivotal for academic success in mathematics [David H. Uttal 2013].

In summary, this paper advocates for the adoption of visualization tools and 3D technologies in educational settings, not only to facilitate the learning of complex mathematical concepts but also to prepare students for future challenges across various fields of knowledge.

The rest of the paper is structured as follows: Section 2 discusses some related work; Section 3 presents Geometrix ideas and functionalities; Section 4 introduces the methodology of the work; Section 5 shows the results; and Section 6 presents the conclusions of the work.

2. Related Work

It is well-known that, in the educational context, the ”standard environment” of the classroom, where the teacher uses a blackboard and marker, is not always the most suitable for teaching certain subjects, especially those involving practical learning. This is particularly true for subjects such as Physics and Chemistry, where using a laboratory to demonstrate real-world phenomena can generate much more engagement from students, potentially leading to better learning outcomes. However, practical subjects are not the only ones that benefit from this approach; abstract and difficult-to-visualize content also requires special attention. Consequently, computer graphics and 2D and 3D visualization tools are gaining prominence and are being increasingly explored by educators.

In this context, considering the teaching of mathematics, standard educational tools like GeoGebra have been widely adopted due to their versatility and ability to make learning more interactive. GeoGebra is a dynamic mathematics software that integrates various mathematical concepts into a single, easily accessible environment, attracting teachers seeking an accessible alternative to traditional methods. A study suggests that using GeoGebra in the classroom can result in more dynamic, creative, and enjoyable learning experiences for students [Machado et al. 2019]. The study concludes by highlighting the potential of such tools to assist in teaching.

However, the ease of access and the range of possibilities offered by software like GeoGebra come with a counterbalance: the learning curve and the effort required to create animations. Other approaches involve more specific software to focus on particular content areas, thus, reducing the complexity for the users and reducing the learning time. A study conducted at the Federal University of Rio de Janeiro [Monzon and Gravina 2013] on teaching complex numbers, proposes a proprietary tool that allows students to visualize operations with complex numbers in a two-dimensional Cartesian plane. The researchers concluded that using this software not only helped students better understand complex number concepts but also increased their interest and motivation to explore related topics. The graphical visualization of complex number operations and transformations provided crucial visual support.

Following this line of thought, it is possible to combine the previously addressed concepts of 2D and 3D animations and software designed for specific content. This rationale underpins the study [Yu-Sheng Su 2022], in which the researchers address three specific geometry problems involving triangles. Positive aspects of this study include mapping student behavior during software use, an idea that, if well executed, provides teachers with insights to better approach the subject matter. The study [Yu-Sheng Su 2022] concludes that students who used the software achieved better results and reported a sense of accomplishment upon completing each stage. Furthermore, the study subtly addresses the concept of gamification, suggesting that, if correctly explored, gamification could be added to such tools, generating even more engagement and interest from students.

In summary, the integration of visualization tools and software tailored to specific content areas has shown promising results in enhancing student understanding and motivation in mathematics education. These tools have the potential to make learning more engaging and interactive, addressing a variety of mathematical concepts in innovative ways.

3. Geometrix: An Educational Software for Geometry Learning

In this section, we will describe the functionality of the Geometrix software, the workflow that students should follow, and how the project design was conceived to achieve the desired results (Figure 2).

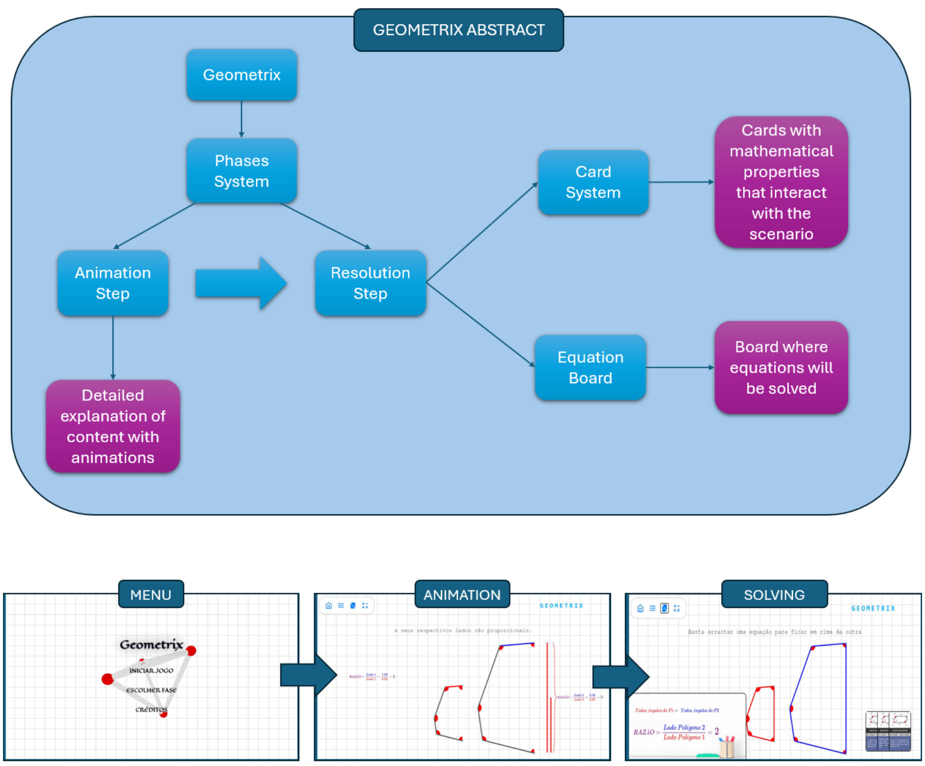

Figure 2. Workflow for the Geometrix Software.

3.1. Main Menu and Concepts

Geometrix is an educational software developed by our research group, utilizing advanced technologies such as Three.js, JavaScript, and WebGL to run seamlessly in standard browsers. Its primary focus is on geometry content, utilizing both 2D and 3D animations to bring complex concepts to life. The design philosophy behind Geometrix is to maintain student attention and focus, achieved through a simple yet attractive interface that minimizes visual distractions.

The initial screen of Geometrix features a straightforward menu that allows users to navigate between levels, complemented by an animated background designed to pique student interest. This approach sets the stage for an engaging learning experience that combines simplicity with visual appeal (Figure 3).

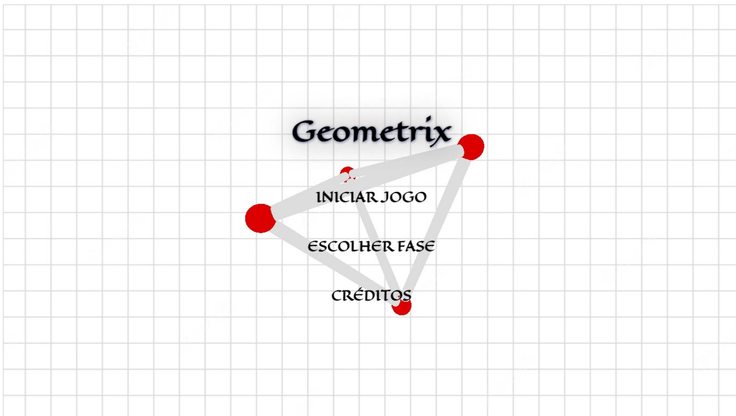

Figure 3. Geometrix main menu.

3.2. Animations

The levels in Geometrix are thoughtfully designed to teach content enjoyably. Each level follows a structured approach that includes an animation detailing the geometric concepts and a problem-solving phase where the student applies what they have learned. The animations are crafted to gradually introduce subtopics, such as the similarity of angles and sides in triangles, leading to a comprehensive understanding of the concepts (Figure 4).

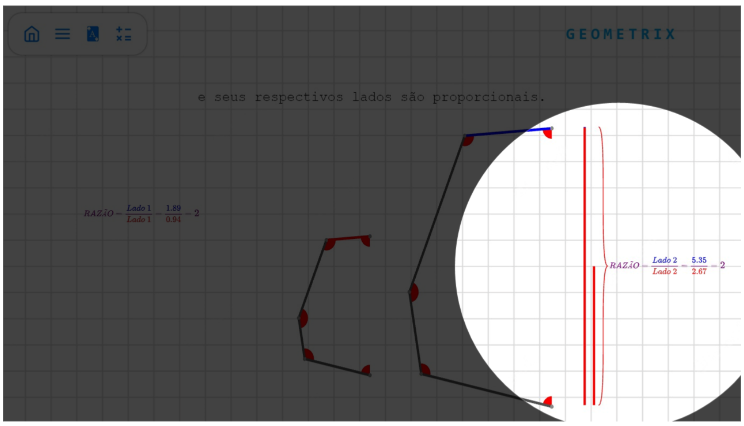

Figure 4. Animation showing the correlation between two polygons.

To prevent the animation phase from becoming monotonous, interactive elements are interspersed throughout. These allow students to make small changes to the scenario, like adjusting angles or resizing triangles, ensuring active participation even during the animation process (Figure 5).

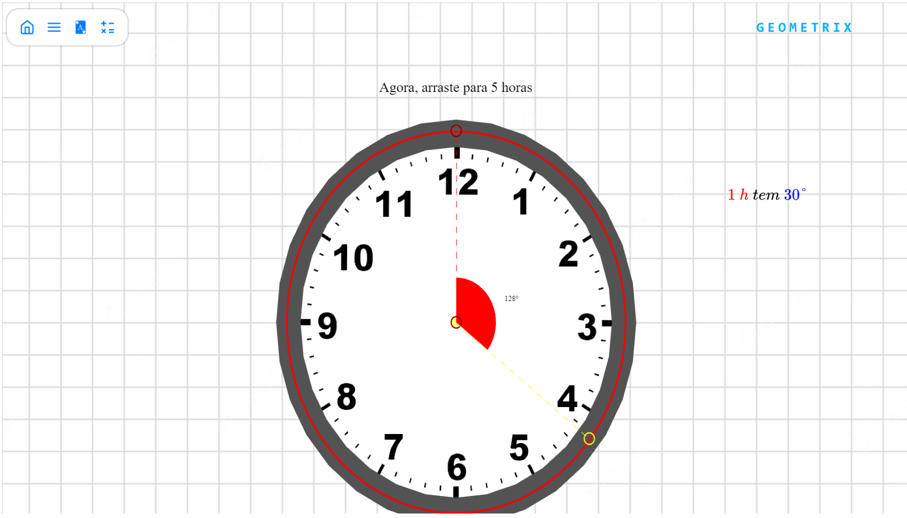

Figure 5. User interacting with animation step.

3.3. Playability

The problem-solving stage of Geometrix is where the software's interactive capabilities are most evident, offering students various methods to engage with the scenario. They can manipulate points to modify geometric shapes, apply operations to specific points, or interact directly with the equation board. The card system is a unique feature that enables students to apply theorems or formulas to geometric objects or equations, facilitating progression through the level in a logical sequence.

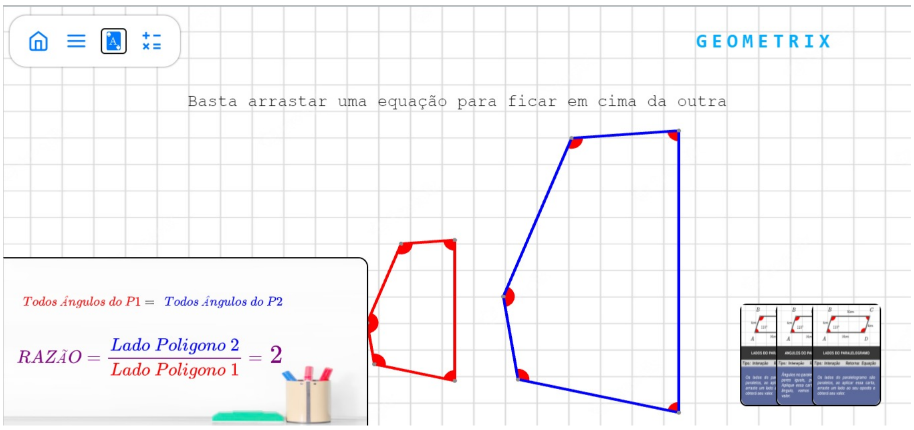

Figure 6. Example of a phase in the playable state.

Should a student select a card that does not apply to the current context, a feedback mechanism is triggered, guiding them toward a more appropriate solution (Figure 6). This approach fosters a learning environment that encourages exploration and reflection, which are essential components of effective learning.

In summary, Geometrix is not merely an educational tool; it is a platform that provides an immersive and interactive learning experience, utilizing animations and gamification elements to enhance understanding and engagement in the realm of geometry education.

4. Methodology

The purpose of this study is to determine if graphical visualization tools could enhance geometry learning among high school students. We designed the study to compare traditional teaching methods with those using interactive technology, specifically the Geometrix software developed by our research group.

In this section, it will be explained how the study's methodology was planned and executed, taking into account topics such as participant selection, materials used, the procedures for data collection that will be used to analyze the results, and how this data will be utilized.

4.1. Participant Selection and Sampling

We selected participants from two high school classes at a public school, involving approximately 60 students aged 15 to 17. Due to the limited sample size, we did not divide the students into control and test groups. Instead, all students underwent the same evaluation and testing procedures when using the software.

4.2. Materials and Tools

The primary tool for this study was Geometrix, the software we used to conduct the research. Additionally, we utilized Google Forms to collect data, allowing students to provide feedback on their user experience. The collaborating teacher provided access to a computer lab, where students could use the software and complete the form.

4.3. Data Collection Procedures

Both groups of students completed pre-test exercises to assess their prior knowledge without the influence of the software. Following this, students participated in a session in the computer lab to use the software, with guidance from the collaborating teacher and a researcher. After this stage, students took post-test exercises with questions of the same level as the pre-test. They also completed a questionnaire about the usability and perceived effectiveness of the game.

4.4. Data Recording

We recorded data through the grades obtained in the pre-test and post-test exercises and the form students filled out after using the software. The session with the game was monitored to ensure engagement and correct use of the software. To protect student anonymity, the collaborating teacher provided the results of the pre- and post-test without revealing student identities, and the form data was also collected anonymously.

5. Results

The results of our study were measured through pre-test and post-test exercises, focusing on triangle similarity, and a questionnaire evaluating the students' experience with Geometrix. A total of 46 students participated in the study.

5.1. Tests

Initially, students completed pre-test exercises in the classroom, consisting of two multiple-choice questions. Students who answered correctly and provided coherent calculations scored 100%, while those who only provided the correct answer without proper development scored 50%, and incorrect answers received 0%.

The average score in the pre-test was 71.2%, which improved to 81.7% in the post-test, indicating a substantial improvement in student performance. Although the test schema is somewhat simplistic, it can help indicate that student interest and motivation can help in overall performance.

5.2. Form

After using Geometrix, students completed a questionnaire to evaluate various aspects of the system. The questionnaire covered usability, effectiveness, engagement, and a comparison with traditional teaching methods.

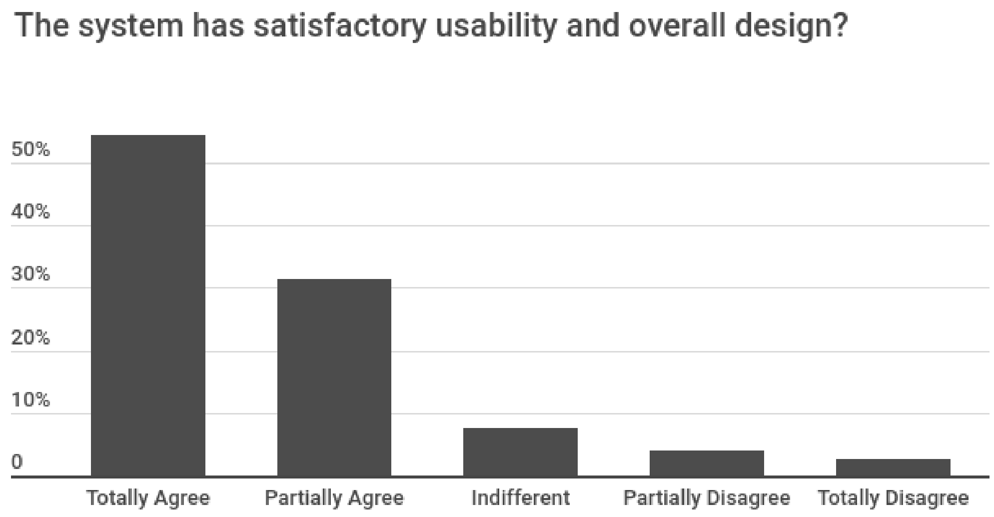

Figure 7. Usability and overall design.

Students rated the system's usability highly, appreciating the interface, design, responsiveness, and ease of use. They also positively assessed the effectiveness of the system, particularly in understanding the taught concepts and the applicability of the software to their learning.

The distinctive features of Geometrix, such as the gamification using the equation board and interactive cards for problem-solving, received about 90% approval (Figure 8). The use of animations for content explanation at the beginning of each stage was also well-received, with approximately 85% approval (Figure 9). In terms of engagement, the questionnaire revealed that students were highly motivated and interacted with the content in a more immersive manner (Figure 10).

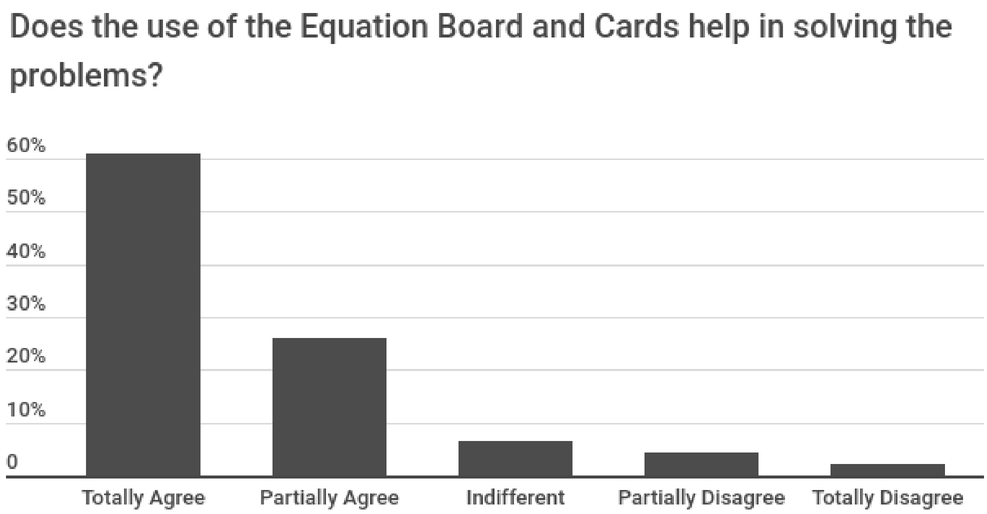

Figure 8. Results of overall favorability for Equation Board and Cards use

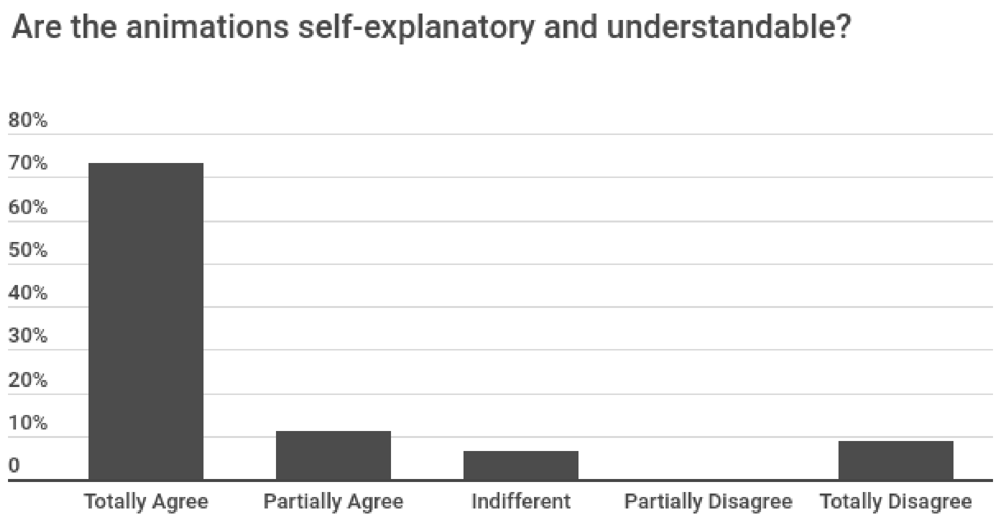

Figure 9. Results of overall favorability for the Animation style used in Geometrix

Furthermore, students reported a preference for learning geometry using Geometrix, with almost 90% indicating a preference for the software over traditional methods (Figure 11). This finding underscores the software's excellent performance in engaging students and providing an immersive learning experience.

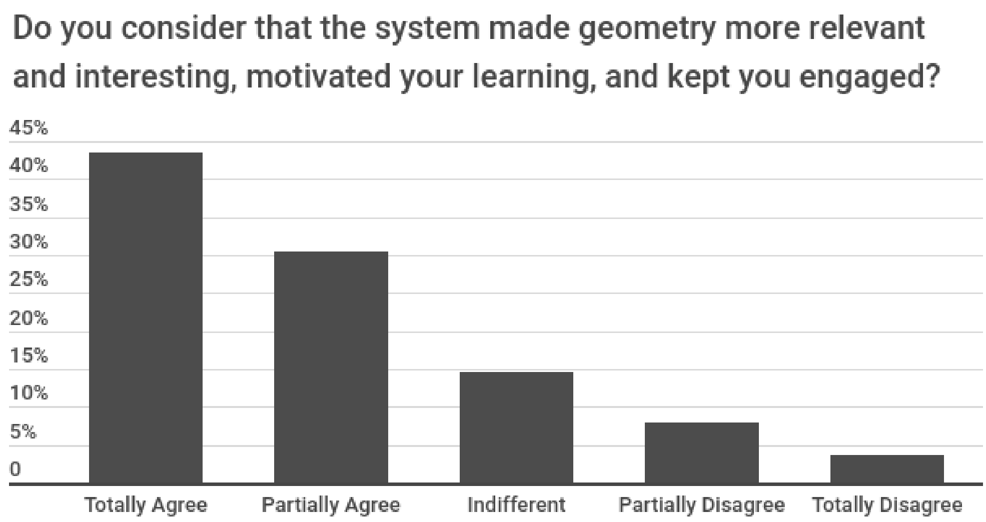

Figure 10. Results of students' opinions on Motivation while using Geometrix

In summary, the results of our study demonstrate that Geometrix is a valuable tool for enhancing geometry education, as evidenced by improved test scores and high student satisfaction. The software's design, which incorporates gamification and interactive elements, contributes to a more engaging and effective learning process.

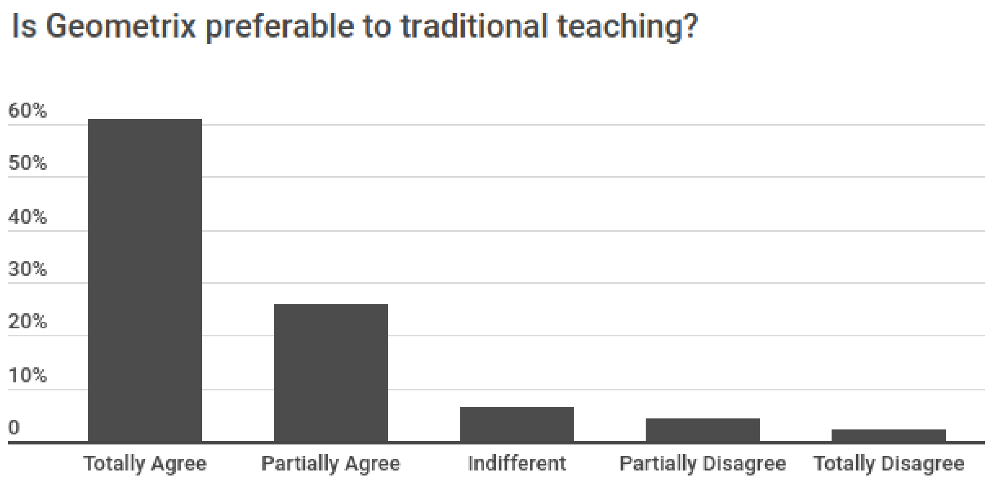

Figure 11. Results of overall software Approval by students

6. Conclusion

Our study demonstrates that the use of Geometrix, a software integrating gamified 2D and 3D animation tools, significantly enhances high school students' learning experience in geometry. The positive reception of the software's features, such as interactive cards and animations, and the noticeable improvement in test scores, underscore the educational potential of these tools. The high preference for Geometrix over traditional methods, expressed by nearly 90% of the students, highlights the software's effectiveness in engaging students and promoting a deeper understanding of geometric concepts.

The contributions of this paper include the development of innovative educational software, Geometrix, and the empirical evidence supporting the integration of visualization tools and gamification techniques in mathematics education. Our findings suggest that these methods can serve as alternative teaching strategies for educators seeking to increase student interest and engagement.

Future work could explore the long-term effects of Geometrix on student performance and its applicability to other areas of mathematics beyond geometry. With more time dedicated to the study and with the software being ready from the beginning, it would be possible to divide students into control groups and conduct additional tests to measure the effectiveness of the approach proposed by Geometrix.

Additionally, further research could investigate the impact of Geometrix on different age groups and educational levels, as well as its potential to address specific learning difficulties in mathematics. Finally, considering the rapid advancement of technology, future studies might also explore the integration of emerging technologies with educational software to enhance learning experiences further.

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