

## EVALUATING THE EFFECTIVENESS OF INTERACTIVE LEARNING TECHNOLOGIES IN ENHANCING SPATIAL THINKING AMONG MATHEMATICS STUDENTS

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### Abstract

The study's purpose was to assess the impact of combining traditional and interactive teaching methods on students' capacity to visualise, manipulate, and transform three-dimensional objects, while also improving their spatial representation and problem-solving skills in geometry. The research monitored 132 students studying mathematics of varying proficiency levels over a semester, employing spatial imagination tasks to improve visualisation abilities. Pre- and post-assessments measured enhancements in spatial reasoning. Methods integrated interactive tools (3D modelling, simulations) with conventional geometry tasks. The study revealed that students using interactive teaching methods, including 3D modelling and computer simulations, exhibited markedly superior enhancements in spatial reasoning relative to those adhering to conventional methods. The experimental group, utilising interactive tools, attained superior scores in spatial thinking assessments, with 60% of students exceeding 70 points, in contrast to merely 35% in the control group. Furthermore, students in the experimental group indicated reduced task complexity and increased satisfaction with the learning methodologies. The findings indicate that interactive methods significantly improve students' capacity to visualise and manipulate geometric entities, thereby enhancing their spatial reasoning abilities. This study demonstrates that a combination of traditional and interactive teaching methods enhances the spatial skills essential for successful mathematical training.

**Keywords** 3D Visualization, Active Teaching Methods, Cognitive Development, Educational Approaches, Spatial Perception.



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## INTRODUCTION

Spatial thinking is one of the key components of mathematical education, as it enables students to visualise, analyse, and manipulate three-dimensional objects. This ability is essential for successfully

solving geometric problems and constructing mathematical models. Despite its significance, many students struggle to develop spatial thinking skills, highlighting the need for effective teaching methods to enhance this ability.

Spatial thinking accompanies individuals throughout life. People live and move within three-dimensional space, where objects occupy specific positions, continually influencing their actions and decisions (Aviv et al. 2024b; Jalmasco, Loberes, & Lasala, 2025; Jarnawi et al., 2025; Intharit, Navarro, & Chanudom, 2025). It is not only a means of acquiring information but also a powerful tool for formulating problems and finding solutions. By enabling individuals to create mental representations of objects and manipulate them in their minds, spatial thinking significantly simplifies the processes of analysis and problem-solving across various contexts (Anugradia, Kruehong, & Alvarez, 2025; Barbagallo et al. 2025; Beltran, 2025; Candia et al., 2025). This ability is crucial in numerous professions, particularly in architecture, engineering, medicine, design, and scientific research. Proficiency in spatial reasoning allows specialists not only to visualise future objects but also to accurately calculate their parameters and structural properties, which is fundamental to achieving success in professional practice (Gilligan 2020; Ikhsan et al., 2025; Shagembe, Issa, & Azlifa, 2025; Syahrul et al., 2025).

The formation of students' scientific concepts and understanding of space, as well as the development of spatial thinking, is one of the most important aspects of intellectual development. Since spatial thinking is primarily cultivated through the study of geometry, this issue becomes particularly relevant when refining the methodology of geometry education (Matieva & Borboeva 2019; Antwi, Gyamera, & Abdulshakur, 2025; Nou et al., 2025; Siddique, Nahar, & Mahmood, 2025). Significant contributions to this field have been made by researchers such as Dalarsson & Dalarsson (2015), who examined the relationship between spatial perception and mathematical proficiency in students. Their study demonstrated that spatial thinking directly influences success in solving mathematical problems and analytical tasks. Their findings provided new insights into how cognitive abilities related to spatial reasoning can enhance mathematical skills, particularly in working with abstract and visual models – an essential aspect of mathematics education.

An important role in the study of spatial thinking was also played by research conducted by Verdine et al. (2019), which identified a correlation between spatial model-building abilities and mathematical competence. Their findings suggest that spatial skills contribute to modelling and problem-solving abilities, including the creation and manipulation of mathematical and geometric objects. These skills are particularly beneficial in educational and research-based activities, reinforcing the significance of spatial thinking in mathematical learning and inquiry.

A notable study by Mix et al. (2019) demonstrated that spatial thinking and mathematical skills form structural interrelationships, where each element supports the development of the other. Spatial thinking specifically entails the capacity to visualise, manipulate, and transform objects mentally, which is crucial for comprehending geometric and mathematical concepts. Mathematical competencies, including problem-solving and mathematical reasoning, frequently depend on spatial abilities to comprehend and address spatially intricate issues (Salah 2016; Amourah et al. 2024; Kheang, Hankhantod, & Wesonga, 2025; Mabeza, 2025). The interrelationships are cognitive and skill-based, engaging overlapping neural pathways that govern visual-spatial processing and mathematical reasoning. This connection is directly associated with augmenting the efficacy of the educational process for mathematics students, as visual illustrations and interactive pedagogical techniques enhance both understanding and problem-solving capabilities in mathematics.

A significant contribution to the theory and practice of spatial thinking was made by the work of İrem İleri et al. (2023), which established that spatial thinking skills can be trained and adapted. These findings are particularly relevant for mathematics students, as the ability to mentally manipulate three-dimensional objects directly contributes to their success in mathematics and engineering disciplines. The research conducted by Hawes et al. (2022) highlighted that targeted training enhances spatial thinking skills and facilitates the development of mathematical abilities, including the analysis and synthesis of geometric structures. This has valuable implications for improving teaching methodologies and research activities for students specialising in mathematics.

Similarly, the study by Cheng & Mix (2014) emphasised that spatial learning improves mathematical proficiency, particularly when instruction incorporates visual and three-dimensional models. The use of such teaching methods enables students to better comprehend abstract mathematical concepts and simplifies the process of solving complex mathematical problems. Furthermore, Hawes et

al. (2019) demonstrated that spatial thinking and numerical perception share a common cognitive foundation. This study is particularly valuable for analysing the neural mechanisms underlying spatial thinking, as it provides insights into the specific areas of the brain activated when solving mathematical problems and working with spatial objects. Such findings are essential for advancing teaching methodologies in mathematics and engineering disciplines.

Teaching methods that integrate both traditional and interactive approaches have the potential to enhance the development of spatial thinking in mathematics students more effectively. Interactive techniques, such as 3D modelling, computer simulations, and the visualisation of geometric objects, offer students not only a deeper understanding of theoretical concepts but also practical application, thereby fostering the development of spatial imagination (Ushenko et al., 2011; Medina Herrera et al. 2019; Yulianti, & Awingan, 2024; Putri et al., 2025).

Given these considerations, further research is needed to determine how the combination of traditional and interactive teaching methods can contribute to the more effective development of spatial thinking in mathematics students. The study aimed to investigate the effects of a combined approach that merges traditional and interactive teaching methods on the enhancement of spatial reasoning in mathematics students, particularly focusing on their capacity to visualise and manipulate three-dimensional objects and solve geometric problems.

## RESEARCH METHOD

The study on the spatial thinking of mathematics students was conducted at the Department of Algebra and Geometry of Authors Institute over one academic semester, from January to June 2024. The primary objective of the research was to evaluate the effectiveness of a combined teaching approach that integrates both traditional and interactive methods for developing students' spatial thinking. The study was structured into several stages, each designed to assess the impact of different teaching methods.

In the first stage, a sample of 132 mathematics students was selected. The sample was representative based on the following criteria: age (ranging from 18 to 22 years), gender (29 men and 103 women), and prior mathematical training. The disbalanced gender distribution in the study may restrict the generalisability of the findings, as the sample may not sufficiently represent the wider public. The study's emphasis on spatial reasoning and mathematical abilities, which are not intrinsically linked to gender, partly alleviates this concern. The students were then divided into two groups: control and experimental. The control group received instruction exclusively through traditional methods, such as lectures and seminars, maintaining the conventional learning format. Meanwhile, the experimental group engaged with interactive teaching methods, including 3D modelling and computer simulations, enabling students to visualise complex mathematical objects in three-dimensional space. This approach allowed for an analysis of the impact of modern teaching methods on the development of spatial thinking and students' ability to visualise geometric objects.

The second stage of the study involved testing students' spatial thinking abilities both before and after the experiment. To assess the initial and final levels of spatial thinking, specialised tests were employed, comprising tasks related to the visualisation of geometric figures, spatial transformations, and the analysis of three-dimensional structures. These tests were administered to both the control and experimental groups, allowing for an objective comparison of results and an evaluation of the impact of each teaching approach. Additionally, a questionnaire was conducted to evaluate students' satisfaction with the learning process, their perception of task complexity, and their views on the efficacy of traditional and interactive teaching methods. A total of 132 questionnaires were gathered, comprising 72 from the control group and 60 from the experimental group. Students evaluated task difficulty and their confidence in addressing spatial thinking tasks using a five-point scale, where 1 signified "very difficult" or "ineffective" and 5 denoted "very easy" or "very effective". Questions included:

- Please rate the difficulty of the tasks in this course on a scale from 1 to 5.
- What was your level of confidence in addressing the spatial reasoning tasks? (1 = Very unconfident, 5 = Very confident)
- Did you observe a rise in task complexity over time? (Yes/No)
- Was the visualisation of 3D objects more arduous with conventional methods compared to interactive techniques? (Yes/No)

Furthermore, students assessed the efficacy of interactive methods (e.g., 3D modelling, simulations) versus traditional methods (e.g., lectures, seminars), contemplating how interactive

techniques augmented their capacity to visualise three-dimensional objects and whether the integration of both approaches enhanced their spatial reasoning abilities. They also conveyed their preferences regarding pedagogical approaches, engagement with tools such as AutoCAD and GeoGebra, and the influence of interactive methods on their motivation and learning results. Included sample enquiries:

- On a scale of 1 to 5, how effective were interactive teaching methods (such as 3D modelling and simulations) in improving your comprehension of the material?
- Did the integration of traditional and interactive methods enhance your spatial reasoning abilities? (Yes/No)
- To what extent did utilising tools such as AutoCAD and GeoGebra augment your educational experience? (1 = Not at all, 5 = Very much)

The interactive techniques involved students from experimental group utilising tools such as AutoCAD, 3ds Max, and GeoGebra to interact with three-dimensional models and geometric simulations. Students utilised AutoCAD and 3ds Max to create and manipulate 3D geometric forms, including cubes, spheres, and pyramids, to visualise and resolve intricate spatial challenges, such as calculating volume or surface area. For instance, the assignment to create a building floor plan in AutoCAD required students to consider spatial relationships and dimensions. Students utilised GeoGebra, a dynamic geometry software, to simulate transformations of shapes, including rotations, reflections, and scaling, while investigating geometric concepts such as congruence and similarity in real-time. These tools enabled students to directly engage with and manipulate geometric objects, thereby improving their ability to visualise three-dimensional structures and address associated mathematical challenges.

In the third stage, a comparative analysis of the results from both groups was conducted to evaluate the effectiveness of the different teaching methods. The Student's t-test was used to process the data, revealing that the experimental group, which engaged with interactive methods, achieved significantly higher results than the control group. This statistically significant difference confirmed the positive impact of the combined teaching approach on the development of spatial thinking. Additionally, the Mann-Whitney U-test was applied to identify differences in task perception between the groups, particularly in terms of visualising complex objects and their transformations. All data were systematically organised and presented in tables and graphs, allowing for a clear comparison between traditional and interactive teaching methods.

## RESULTS AND DISCUSSION

The results of the initial spatial thinking assessment provided insights into the baseline proficiency of the students participating in the study. Testing was conducted among students in two groups: a control group and an experimental group. The control group comprised 72 students, while the experimental group included 60 students. The control group was taught using traditional methods, such as lectures and seminars, without the incorporation of interactive technologies. In contrast, the experimental group engaged with interactive teaching methods, including 3D modelling and computer simulations.

During the initial assessment, students completed tasks involving the visualisation of geometric figures, transformations of three-dimensional objects, and problem-solving tasks requiring spatial reasoning. The average score for the control group at the beginning of the training was 45 out of a possible 100, while the experimental group achieved a slightly higher average score of 48. However, the difference between the groups at this stage was minimal and statistically insignificant, indicating that students in both groups had approximately the same level of spatial thinking development at the outset.

Figure 1 presents the results of the initial spatial thinking assessment for students in both the control and experimental groups. This comparison allows for an evaluation of the students' initial skill levels and provides a basis for analysing the impact of different teaching approaches.

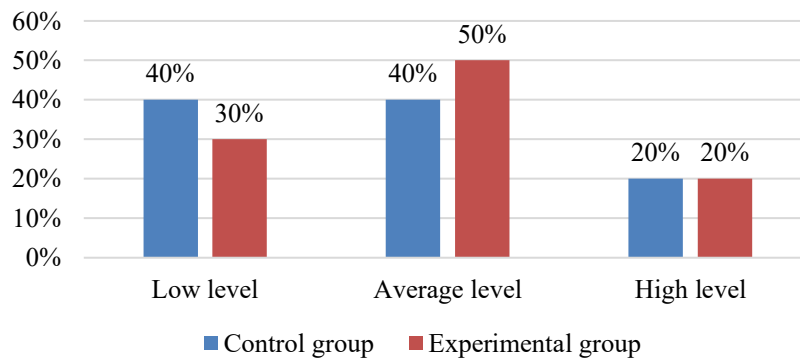


Figure 1. Results of testing spatial thinking at the beginning of training for the control and experimental groups

The figure above illustrates the average test results of both groups at the beginning of the experiment. The analysis indicated that roughly 40% of students in the control group scored below 40 points on the spatial thinking tests, signifying a deficient level of development of this cognitive skill among a substantial portion of participants. In the experimental group, this proportion was marginally lower, with approximately 30% of students attaining scores below 40 points, indicating a slight advantage in the initial training level. A chi-square test for independence was conducted to evaluate the statistical significance of this difference. The results produced a chi-square value of 2.54 and a p-value of 0.28, exceeding the conventional significance threshold of 0.05. Consequently, the initial disparity between the control and experimental groups during the training was not statistically significant, and the overall average levels of spatial thinking remained comparable between the two groups.

The comparative analysis also demonstrated that both groups included students with a high level of spatial thinking. Approximately 20% of participants in both the control and experimental groups scored above 60 points, indicating the presence of students with well-developed cognitive abilities, particularly in visualisation and working with three-dimensional objects. This distribution provided a more objective basis for the subsequent comparison of results after the completion of the experiment, as it included both students with initially low spatial thinking abilities and those who demonstrated a high level of proficiency from the outset. This diversity ensured that all students had the opportunity to show progress in mastering the material.

These findings highlight the importance of spatial thinking for students encountering mathematical problems that require the representation and manipulation of three-dimensional objects. The results of the initial testing indicated that students with high spatial thinking scores were already more adaptable and proficient in solving problems involving spatial representation and object manipulation at the early stages of their studies. This skill enhances their ability to approach tasks related to construction, transformation, and visualisation of objects, particularly in academic disciplines that demand a strong understanding of three-dimensional concepts.

Conversely, students with lower initial scores experienced greater difficulties, underscoring the need for more active and targeted development of spatial thinking skills within the learning process. Spatial reasoning is essential for mastering a wide range of disciplines, from engineering and architecture to advanced mathematical problem-solving, and a deficiency in this skill can impede academic performance and hinder problem-solving abilities. To support students with lower initial scores, more personalised approaches should be implemented. For instance, additional modules focusing on 3D modelling or interactive exercises involving virtual objects could be introduced to reinforce spatial skills through practical engagement (Herawati and Hariyani 2024).

Equally significant is the high percentage of students in both the control and experimental groups who demonstrated considerable potential for further development. Approximately 20% of students scored above 60 points in the initial testing, indicating well-developed spatial thinking abilities that provide a strong foundation for future academic achievement. These students are likely to excel in both abstract and practical problem-solving tasks that require the visualisation and manipulation of objects in space. This level of readiness presents additional opportunities for the implementation of innovative teaching methods aimed at deepening knowledge and fostering interest in subjects related to spatial concepts.

Furthermore, the study’s findings highlight the importance of not only developing but also purposefully strengthening spatial thinking across students with varying levels of prior preparation. Spatial reasoning is a key factor in academic success in mathematics, engineering, and other disciplines that demand high levels of abstract and logical thinking (Prontenko et al., 2019; Neguliaieva 2024; Rachmatika, & Salighehdar, 2024; Somantri, 2024). To enhance the development of this skill more effectively, a flexible learning approach can be integrated into educational programmes, allowing students with different levels of initial proficiency to progress at their own pace (Uttal et al. 2024).

It is also advisable to consider the implementation of various methods for monitoring and assessing spatial thinking. For example, tests involving the visualisation of three-dimensional objects, tasks focused on constructing and transforming shapes, and exercises incorporating elements of spatial analysis would enable educators to better evaluate students’ comprehension of the material (Horvat & Kuzma-Kachur 2025). Conducting such assessments regularly would not only facilitate the monitoring of spatial thinking development but also allow for timely adjustments to curricula to optimise learning outcomes for students at all proficiency levels (Liu et al. 2020; Jumaera et al., 2024; Rubio et al., 2025).

Thus, the findings of this study provide a clear understanding of students' spatial thinking abilities and reaffirm the necessity of further developing this skill. Students with high initial proficiency in spatial reasoning have a significant advantage when studying disciplines that involve spatial concepts, granting them greater opportunities for future academic and professional success (Diachuk 2024; Kuznietsov & Kuznietsova 2024). Conversely, for students with less developed spatial thinking abilities, educational institutions should offer additional support through visualisation and modelling exercises to ensure equal opportunities for successfully mastering the subject (Uttal & Cohen 2012; Salim et al, 2025; Obenza et al., 2025).

The overall testing results indicated that both groups had a comparable level of proficiency at the initial stage of the experiment. This created favourable conditions for further research, as a similar baseline skill level in both groups allowed for an objective assessment of the impact of different teaching methods on the development of spatial thinking. Following the completion of the educational process, which spanned one semester, a final assessment of spatial thinking levels was conducted among students in both the control and experimental groups. The objective of this testing was to evaluate the effectiveness of the teaching methods employed and to compare the outcomes of students who followed traditional approaches with those who engaged in interactive learning methods.

The results of the final assessment revealed significant improvements in spatial thinking abilities among participants in both groups. Figure 2 presents the post-training spatial thinking test results for students in the control and experimental groups. These data provide a clear basis for evaluating the impact of the teaching methods used on the development of spatial thinking in each group.

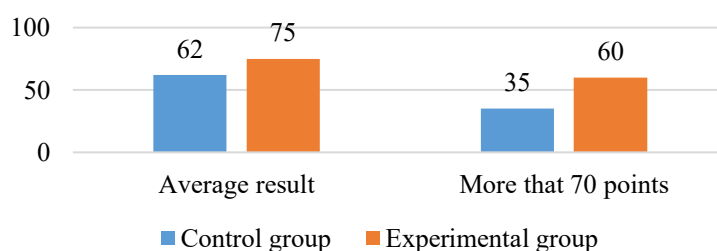


Figure 2. Results of testing the level of spatial thinking after completion of training in the control and experimental groups

The control group, which was taught using traditional methods, achieved an average score of 62 out of a possible 100. While this indicates progress in the development of spatial thinking, it remained lower compared to the experimental group, which attained an average score of 75 out of 100. The experimental group, which engaged with interactive teaching methods such as 3D modelling and computer simulations, demonstrated significantly higher results, highlighting the effectiveness of these approaches in comparison to traditional methods.

An analysis of the post-training results revealed that 60% of students in the experimental group scored above 70 points, indicating a high level of proficiency in spatial thinking skills. In contrast, only 35% of students in the control group achieved similar scores, reflecting a comparatively slower

development of this cognitive ability. It is important to note that both groups exhibited progress; however, the rate of improvement in the experimental group was considerably more pronounced.

Through the use of interactive teaching methods, students in the experimental group not only gained a better understanding of the theoretical material but also had the opportunity to directly interact with three-dimensional objects, which significantly enhanced the development of spatial thinking. Students who engaged with 3D modelling programmes achieved results that were 25% higher than those of students who relied solely on traditional teaching methods. This suggests that interactive approaches enable deeper immersion in the learning process and facilitate the manipulation of three-dimensional objects. Although students in the control group also demonstrated progress, their improvement was less pronounced. The average score of the control group increased to 62 points after completing the training, which represents a 17-point increase from the initial assessment. However, this progress remained lower compared to the experimental group. Additionally, only 20% of students in the control group achieved scores above 80 points, indicating that traditional teaching methods do not always foster the optimal development of spatial thinking. The overall analysis demonstrated that interactive teaching methods have a significant impact on the development of spatial thinking, enabling students not only to assimilate theoretical material but also to apply it in practice.

Following the final assessment, students in both the control and experimental groups completed questionnaires in which they evaluated their subjective perception of task complexity and the effectiveness of the teaching methods used. The objective of this stage was not only to assess the quantitative development of spatial thinking but also to understand how students themselves perceived different teaching approaches, particularly interactive and traditional methods. The questionnaire provided insights into key aspects of students' interaction with educational material and their ability to adapt to new learning methodologies.

Students in the control group, who were taught using traditional methods, rated the difficulty of the problems at an average of 3.5 out of 5. This suggests that many students found the tasks challenging, potentially due to difficulties in visualising complex three-dimensional objects. Regarding the perceived effectiveness of traditional methods, the average rating was 3.2, indicating moderate levels of student satisfaction. Some students reported struggling to understand geometric concepts without additional visual aids. In contrast, the results were significantly higher in the experimental group. Students who engaged with interactive teaching methods rated the difficulty of the problems at 4.2, suggesting that interactive approaches, particularly 3D modelling and computer simulations, made problem-solving more accessible, comprehensible, and visually intuitive. In terms of the effectiveness of the methods, the experimental group provided a notably higher rating of 4.5, reflecting significantly greater satisfaction with interactive teaching techniques. Many students highlighted that the ability to directly interact with three-dimensional objects greatly enhanced their understanding and retention of the educational material.

Table 1 presents the survey results from students in both the control and experimental groups, allowing for an analysis of their perceptions of the teaching methods used, as well as their subjective evaluation of task complexity and the overall effectiveness of the learning process.

Table 1. Results of the survey of students in the control and experimental groups

Group	Task difficulty rating (out of 5)	Evaluation of the methods effectiveness (out of 5)
Control group	3.5	3.2
Experimental group	4.2	4.5

As the Table 1 illustrates, students in the experimental group achieved significantly higher scores in both perceived task complexity and the effectiveness of teaching methods. This confirms that interactive teaching methods, such as 3D modelling, greatly facilitate the comprehension of complex geometric objects and enhance students' ability to learn and retain the material.

Students in the control group frequently reported difficulties in visualising three-dimensional objects and completing tasks without the aid of visual representations. While they rated these tasks as moderately difficult, many noted that additional explanations or visualisations were necessary for a full understanding. In contrast, students in the experimental group found the same tasks more accessible due to the use of interactive technologies, which enabled them to visualise and manipulate objects in real

time. With regard to the effectiveness of teaching methods, the difference between the control and experimental groups was also notable. Control group students expressed difficulties in understanding abstract concepts, whereas students in the experimental group highly valued the use of technology for working with three-dimensional objects. These findings confirm that interactive approaches significantly improve the quality of learning by making the material more accessible and comprehensible.

A comparative analysis of the results from the control and experimental groups following the completion of the training provided valuable insights into the effectiveness of different teaching methods. The primary objective of this analysis was to identify statistically significant differences between the two groups based on spatial thinking assessments and data collected from student questionnaires. The testing results revealed notable differences between the control and experimental groups. The application of Student's t-test to compare these indicators confirmed that the difference in average scores between the two groups was statistically significant, demonstrating that the influence of different teaching methods was reliable. The t-test value exceeded the critical threshold, thereby supporting the hypothesis that students who engaged with interactive teaching methods exhibited significantly greater improvements in spatial thinking development compared to those who studied using traditional methods.

The analysis demonstrated that while the control group made some progress, it was significantly less pronounced than that of the experimental group. The increase in the average score by 17 points (from 45 to 62) in the control group suggests that traditional teaching methods, although effective, do not facilitate as rapid or profound an understanding of the material as interactive methods. In contrast, the experimental group showed an increase of 27 points (from 48 to 75), indicating that interactive methods, particularly 3D modelling and computer simulations, enabled students to develop their spatial thinking skills far more effectively. This substantial improvement in scores also highlights the potential of interactive methods as a means of enhancing the overall level of students' knowledge and competencies. Interactive technologies provide students with direct engagement with the material, thereby improving their ability to visualise and manipulate objects in space (Kamran et al. 2023).

A significant difference in results was also observed in students' assessments of task complexity and the effectiveness of teaching methods, as expressed in the questionnaire responses. According to the data, students in the experimental group rated the tasks as less complex (4.2 out of 5), whereas students in the control group provided a moderately high complexity rating of 3.5. This suggests that interactive methods facilitated the comprehension of educational material, making it more accessible and easier to understand. Similarly, the perceived effectiveness of teaching methods was notably higher in the experimental group, with an average rating of 4.5 compared to 3.2 in the control group. These findings highlight that the use of interactive methods not only enhances students' learning experience but also increases their overall satisfaction and motivation. The use of computer simulations, for instance, enabled students to gain a clearer understanding of complex concepts and apply them more confidently in practice.

The results of Student's t-test further confirmed that the differences in students' responses regarding task complexity and teaching effectiveness were statistically significant. This suggests that students' subjective perceptions of the learning process align with objective measures of their progress, supporting the overall hypothesis on the benefits of interactive learning. Thus, students' own evaluations of task complexity and teaching effectiveness serve as important indicators of the success of the learning process. Additionally, their feedback on teaching methodologies contributes to the refinement and enhancement of educational strategies, ensuring that instructional approaches are adapted to meet the needs of learners.

Another important aspect of the comparative analysis was the assessment of the performance of students who initially demonstrated weaker results. In the control group, students with lower initial scores improved their results by an average of 20%, representing a moderate level of progress. In contrast, students in the experimental group with similar initial results showed an improvement of 35%, highlighting the significantly greater effectiveness of interactive approaches for those requiring additional support in developing spatial thinking. This finding is particularly important, as it demonstrates that interactive methods can effectively compensate for differences in students' levels of preparation, providing all learners with opportunities for development regardless of their starting point.

The Mann-Whitney U-test was used to compare the results of the control group, which was taught using traditional methods, with those of the experimental group, which engaged with interactive

approaches such as 3D modelling and computer simulations. The results confirmed significant differences in spatial thinking development between the two groups following the completion of the educational process. The experimental group achieved significantly higher average scores than the control group, further validating the effectiveness of combined teaching methods. Additionally, the application of the Mann-Whitney U-test revealed that these differences in student performance remained significant even when accounting for factors such as initial level of preparation, learning style, and responsiveness to interactive methods.

The data indicated that students in the experimental group not only achieved higher average scores but also exhibited a more even distribution of results. In particular, significantly fewer students in the experimental group scored below 60 points, whereas such lower scores were more prevalent in the control group. This suggests that interactive teaching methods contribute not only to an overall improvement in spatial thinking but also help to reduce performance disparities between individual students. In contrast, the control group, which relied on traditional teaching methods, displayed greater variations in results, potentially reflecting individual difficulties in mastering the material without additional visual aids.

The findings of this study clearly demonstrate the significant impact of interactive methods on the development of spatial thinking in mathematics students. The use of 3D modelling and simulations enabled students in the experimental group to achieve significantly higher test scores compared to those in the control group, where traditional teaching approaches were employed. These results support the findings of Hegarty et al. (2019), who established that visual and spatial models significantly enhance the acquisition of spatial concepts in STEM disciplines. Their research demonstrated that students who engaged with interactive learning tools achieved higher results and found it easier to grasp complex concepts due to visualisation and the three-dimensional representation of objects.

This study also confirmed that students who utilised interactive methods achieved, on average, 13% higher scores than those in the control group, aligning with the findings of Hinze et al. (2019). Their research highlighted those interactive visual models improve comprehension and retention of material in the exact sciences, fostering a more systematic approach to learning. In this experiment, students who worked with 3D models and computer simulations exhibited a stronger understanding of complex mathematical concepts, further validating the conclusions of Hinze et al. Interactive methods proved particularly effective for students with initially lower levels of spatial thinking. As noted in the study by S.R. Hinze et al., engagement with visual models helps to enhance spatial reasoning skills in students with weaker initial preparation. The findings of this research confirm that interactive approaches play a compensatory role, bridging gaps for students who struggle to comprehend material through traditional methods. Students with lower initial proficiency demonstrated noticeable improvements after utilising interactive technologies, suggesting that such methods are universally beneficial for both highly proficient and less prepared students.

Thus, the findings of this study indicate that the integration of interactive teaching methods, such as 3D modelling and simulations, contributes to the development of spatial thinking and enhances students' overall academic performance. This is particularly important not only for students in mathematical, technical, and engineering disciplines – where spatial reasoning plays a crucial role – but also for broader cognitive development. The adoption of such methods represents a significant step towards modernising educational processes, making learning more aligned with the needs of contemporary students (Teplá et al. 2022).

However, despite the high effectiveness of interactive methods, their implementation requires additional resources. The integration of interactive technologies necessitates appropriate computer equipment, specialised software, and teacher training, all of which may entail significant costs. For the successful incorporation of interactive methods into the educational process, it is essential to consider the support of educational institutions and government agencies (Ascione 2023; Prytyka 2023).

Moreover, while the results of this study demonstrate the considerable effectiveness of interactive methods, their widespread adoption may be constrained by the financial and technical resources available to educational institutions. To overcome these limitations, it is recommended that additional educational and governmental funding be secured to establish the necessary conditions for equipping institutions with modern tools and training programmes.

The findings of this study are also significant for understanding cognitive development in other fields such as engineering, architecture, and design, where spatial thinking plays a crucial role. Interactive technologies, including modelling and simulations, can be adapted to various curricula,

enabling students at different levels of proficiency to acquire spatial skills more effectively and comprehensively. These results underscore the positive impact of integrating interactive technologies into the learning process, as they facilitate the development of key cognitive skills such as spatial reasoning, analytical thinking, and visualisation abilities. Incorporating modern educational technologies into academic programmes not only enhances student performance but also increases engagement and fosters a deeper understanding and appreciation of the subject matter (Davydiuk et al. 2024; Khilya et al. 2024). This is particularly relevant in educational settings, where the primary role of teachers extends beyond imparting knowledge to helping students apply it in practice (Pratama et al. 2023). The use of techniques such as 3D modelling and computer simulations creates a practical learning environment that simplifies complex concepts, enhances comprehension, and improves overall retention of the material (Smetana and Bell 2012; Abduvalieva et al., 2024).

Additionally, interactive teaching methods actively engage the emotional dimension of the learning process. Students who can manipulate virtual objects, conduct experiments, or visualise concepts are more likely to develop enthusiasm for the subject matter, as they can perceive its real-world applications (Aviv et al. 2024a; Spaska et al. 2025). A notable example is 3D modelling, which enables students to create their own projects and witness the transformation of theoretical knowledge into practical solutions. This process not only strengthens students' self-confidence but also motivates them to pursue a deeper understanding of the subject, as confirmed by several studies (Rafiq 2022; Eslit 2023).

The findings of this study reinforce the importance of incorporating interactive technologies into the educational process and highlight their significant contribution to the development of both cognitive and practical skills in students. As the needs of modern learners continue to evolve, educational institutions should endeavour to integrate these methods to better prepare students for real-world professional environments. Future research is necessary to further expand the evidence base on the impact of various interactive teaching methods on students' cognitive development across different disciplines, including mathematics, engineering, and medicine.

## CONCLUSION

The study demonstrated that interactive teaching methods have a significant impact on the development of spatial thinking in mathematics students. In particular, it was found that technologies such as 3D modelling and computer simulations contribute to a substantial improvement in test performance compared to traditional teaching methods. Students who engaged with interactive technologies showed a 13% improvement in test scores, highlighting the effectiveness of these methods. A particularly notable benefit was observed among students with initially lower levels of spatial thinking, who demonstrated significant progress after using interactive approaches. One of the key findings of the study is that interactive teaching methods enhance not only cognitive skills but also students' motivation to learn. Participants in the experimental group highly valued the opportunity to work with three-dimensional models, which made the learning process more visual and comprehensible. This underscores the importance of integrating modern technologies into education to increase student engagement and improve learning outcomes. The study also identified potential challenges associated with the implementation of interactive technologies. While highly effective in developing spatial thinking, their adoption may be constrained by the need for specialised technical equipment and software. This presents a challenge for educational institutions with limited material and technical resources to support such innovations. Additionally, the study was conducted on a limited sample of students from a single educational institution, which may affect the generalisability of the results. Further research with a broader sample across multiple institutions is recommended to strengthen the evidence base and validate these findings. The significance of these findings lies in their confirmation of the effectiveness of interactive technologies in developing key cognitive skills in students, which is crucial for the training of specialists in the field of mathematics. Future research could explore the impact of interactive methods on students across different disciplines, as well as their influence on other cognitive processes, such as critical thinking and problem-solving abilities. A promising direction for further investigation is the adaptation of interactive methods to the individual needs of students, making the educational process more flexible and effective. Additionally, it is essential to examine the long-term effects of these technologies to assess their influence on students' continued academic and professional development. Thus, this study has reinforced the importance of interactive technologies in education, highlighting their role in enhancing spatial thinking and other cognitive skills. Future

research should focus on expanding the sample size, incorporating a wider range of disciplines, and analysing the long-term implications of integrating these technologies into the teaching process.

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### AUTHOR CONTRIBUTIONS

Conceptualization, GB, KS; Methodology and Investigation, MK, GS; Software, Resources, and Data Curation, NS; Writing – Original Draft Preparation, GB, KS; Writing – Review & Editing, GB, KS, MK, GS, NS.

### CONFLICTS OF INTEREST

The author(s) declare no conflict of interest.

### USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors declare that no artificial intelligence (AI) tools were used in the generation, analysis, or writing of this manuscript. All aspects of the research, including data collection, interpretation, and manuscript preparation, were carried out entirely by the authors without the assistance of AI-based technologies.

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