

Spatial Reasoning Outcomes in Technology-Enhanced Geometry Teacher Education

Angelika Schmid¹, Tomas Barot¹, Lilla Korenova² and Zsolt Lavicza³

¹Faculty of Education University of Ostrava, Ostrava, Czech Republic

²Faculty of Education Comenius University Bratislava, Bratislava, Slovakia

³School of Education Johannes Kepler University Linz, Linz, Austria

angelika.schmid@osu.cz

tomas.barot@osu.cz

korenova@fedu.uniba.sk

zsolt.lavicza@jku.at

Abstract: Spatial reasoning is widely recognised as an essential competence for mathematics teachers and a significant predictor of achievement across STEM disciplines. However, less attention has been devoted to how these abilities can be systematically supported through technology-enhanced learning environments in higher education, particularly within teacher education. This study examined spatial reasoning outcomes in a technology-enhanced geometry course designed for prospective mathematics teachers. The research focused on comparing current learning outcomes with delayed performance following previous participation in the course. A quasi-experimental design was employed with two university student cohorts enrolled in geometry teacher education courses. One cohort had completed the course in the previous academic year, while the second cohort was involved in the current implementation during the ongoing semester. The learning environment was based on the Geometry Teaching Model, which integrated manual construction activities with digital technologies, particularly GeoGebra. Four spatial reasoning tests were administered during the semester. The tests assessed three components of spatial reasoning: mental rotation, spatial orientation, and spatial visualisation. Data were analysed using descriptive and non-parametric statistical methods. Students participating in the current course implementation achieved significantly stronger results in several complex tasks requiring reconstruction of three-dimensional objects from two-dimensional representations, interpretation of orthographic views, and advanced spatial synthesis. Students from the previous cohort performed comparably in simpler orientation tasks, suggesting partial maintenance of basic spatial skills over time. However, their performance was weaker in more demanding visualisation tasks. The findings suggest that performance in advanced spatial reasoning tasks may be particularly sensitive to the continuity of structured educational support. Sustained technology-enhanced geometry learning may therefore provide valuable opportunities for supporting complex visual-spatial competences in teacher education. The study contributes to current discussions on e-learning design, competence sustainability, and the preparation of future mathematics teachers in higher education.

Keywords: Spatial Reasoning, Teacher Education, Geometry Education, GeoGebra, Technology-Enhanced Learning.

1. Introduction

Spatial reasoning is widely recognised as a fundamental cognitive competence that plays a crucial role in mathematics education and predicts success across science, technology, engineering, and mathematics (STEM) disciplines (Ramful, Lowrie and Logan, 2017; Uttal et al, 2013). It enables learners to mentally manipulate objects, interpret multiple representations, and understand geometric relationships that are essential for solving mathematical problems. As geometry relies heavily on the ability to visualise, transform, and reason about spatial structures, the development of spatial reasoning has become an important objective of mathematics teacher education. Future teachers are expected not only to develop these competences themselves but also to create learning environments that foster spatial reasoning among their pupils.

Recent advances in digital technologies have created new opportunities to support the development of spatial reasoning through interactive geometry learning environments. Dynamic geometry software enables learners to construct, manipulate, and explore geometric objects while seamlessly moving between two-dimensional and three-dimensional representations. These environments encourage active exploration, immediate visual feedback, and inquiry-based learning, making them particularly suitable for developing spatial reasoning within mathematics teacher education.

Although previous research has demonstrated the educational value of technology-enhanced geometry learning, considerably less attention has been devoted to the long-term sustainability of spatial reasoning following technology-supported instruction. Moreover, relatively little is known about the diagnostic potential of different geometry-specific assessment tasks and their ability to distinguish between varying levels of spatial reasoning performance. Understanding which types of tasks are most sensitive to differences in spatial

reasoning is important not only for evaluating educational interventions but also for designing assessment instruments that capture the complexity of spatial thinking.

To address these issues, this study compares the spatial reasoning performance of two cohorts of prospective mathematics teachers enrolled in the same technology-enhanced university geometry course. One cohort was assessed during the course, whereas the second cohort completed the same assessment approximately one year after instruction, enabling the comparison of current and delayed spatial reasoning outcomes. In addition to comparing the two cohorts, the study investigates which characteristics of geometry-specific assessment tasks most effectively differentiate students' spatial reasoning performance. The instructional context was based on the Geometry Teaching Model (GTM), a technology-enhanced instructional framework integrating digital and manual geometry activities, which is described in Section 2.2. The study addresses the research questions presented in Section 3.1.

2. Theoretical Background

This section provides the theoretical framework underpinning the study. It first examines the concept of spatial reasoning and its key components in the context of mathematics education. Subsequently, it reviews the contribution of technology-enhanced geometry learning to the development of spatial reasoning and introduces the GTM, which served as the instructional context for the reported research.

2.1 Spatial Reasoning

Spatial reasoning is generally understood as the ability to generate, manipulate, transform, and interpret mental representations of spatial relationships between objects and within space. It represents a multidimensional cognitive competence that underpins geometric thinking, supports mathematical problem solving, and contributes to achievement across STEM disciplines. Beyond mathematics education, spatial reasoning is recognised as an important predictor of later academic and professional success, highlighting the need for its systematic development throughout education (Ramful, Lowrie and Logan, 2017; Uttal et al, 2013).

Although several theoretical classifications of spatial reasoning have been proposed, this study adopts the framework developed by Ramful, Lowrie and Logan (2017), which distinguishes three complementary constructs of spatial reasoning that are particularly relevant to school mathematics: mental rotation, spatial orientation, and spatial visualisation. This framework was selected because it reflects the types of spatial tasks commonly encountered in geometry and provides a useful basis for educational assessment.

The three components represent distinct but closely interconnected aspects of spatial reasoning and together capture the range of spatial processes commonly required in geometry education.

- **Mental rotation** refers to the ability to mentally rotate two- or three-dimensional objects while maintaining their structural properties.
- **Spatial orientation** involves mentally changing one's viewpoint or determining the relative positions of objects from different perspectives.
- **Spatial visualisation** encompasses more complex multi-step manipulations of spatial information, often requiring the coordination of multiple representations and successive mental transformations.

Because spatial reasoning comprises multiple interrelated cognitive processes, its assessment requires tasks that capture different forms of spatial thinking rather than relying on a single type of spatial operation (Lowrie et al, 2020). Geometry tasks involving object transformations, orthographic representations, cross-sections, and transitions between two-dimensional and three-dimensional representations provide valuable opportunities for diagnosing different aspects of spatial reasoning. Accordingly, the assessment design of the present study incorporates geometry tasks targeting these complementary components of spatial reasoning, enabling a more comprehensive evaluation of students' spatial reasoning abilities.

2.2 Technology-Enhanced Geometry Learning

Technology-enhanced learning has become an integral part of mathematics education, particularly in geometry, where digital technologies offer new opportunities to support conceptual understanding, mathematical exploration, and the development of higher-order cognitive skills. In this context, interactive learning environments enable learners to construct, manipulate, and investigate geometric objects in ways that are difficult to achieve using traditional static representations alone. These environments encourage active

exploration and inquiry while supporting connections between visual and formal mathematical representations (Duval, 2006).

Among the available digital tools, dynamic geometry software has received particular attention because it enables learners to explore geometric relationships through direct manipulation, immediate visual feedback, and seamless transitions between two-dimensional and three-dimensional representations. GeoGebra, one of the most widely used dynamic mathematics environments, facilitates experimentation with geometric constructions while promoting spatial reasoning through interactive visualisation and multiple representations. Previous research suggests that dynamic geometry environments can support students' conceptual understanding, engagement, and geometric reasoning (Hohenwarter and Lavicza, 2007; Sinclair, Holt and Heyd-Metzuyanim, 2016; Weigand, Hollebrands and Maschietto, 2025).

Building on these principles, the GTM was developed as a technology-enhanced instructional framework for university geometry courses in prospective mathematics teacher education (Schmid and Korenova, 2024). The model integrates dynamic geometry software with manual geometric constructions and complementary learning activities to support the systematic development of spatial reasoning while fostering conceptual understanding of geometry. Rather than relying exclusively on digital technologies, the GTM emphasises purposeful transitions between digital and manual representations, enabling students to approach geometric problems from multiple perspectives. The present study was conducted within this instructional framework.

2.3 Research Questions

To investigate prospective mathematics teachers' spatial reasoning performance through geometry-specific assessment tasks implemented within the GTM, the study addressed the following research questions:

- **RQ1:** How did the quasi-control and quasi-experimental cohorts differ in their performance on geometry-specific assessment tasks targeting different components of spatial reasoning?
- **RQ2:** Which characteristics of geometry-specific assessment tasks appear to be most informative for differentiating prospective mathematics teachers' spatial reasoning performance?

3. Methodology

3.1 Research Design

This study employed a quasi-experimental comparative design involving two cohorts of prospective mathematics teachers enrolled in the *Synthetic Geometry II* course at the University of Ostrava. The first cohort consisted of students who had completed the course during the previous academic year and were assessed approximately one year after instruction, allowing the examination of delayed performance. The second cohort comprised students enrolled in the current course, who completed the same assessment tasks during the semester as part of their regular coursework.

Both cohorts completed an identical set of geometry-specific assessment tasks designed to represent the three components of spatial reasoning: mental rotation, spatial orientation, and spatial visualisation. The assessments were administered under identical conditions, using the same instructions and time limits, to ensure the comparability of the collected data. Each assessment task targeted a specific geometry-related cognitive process associated with one of the three spatial reasoning components.

Beyond comparing students' learning outcomes, the present study draws on the quasi-experimental dataset to examine the characteristics of individual geometry-specific assessment tasks and the extent to which different task types differentiated spatial reasoning performance.

3.2 Participants

The study involved prospective mathematics teachers from two successive cohorts enrolled in the *Synthetic Geometry II* course at the University of Ostrava. The quasi-control and quasi-experimental course cohorts comprised 24 and 16 enrolled students, respectively. Participation in the study was voluntary, and the number of participants varied across the four test administrations. In the quasi-control cohort, Tests 1–4 were completed by 20, 20, 20, and 16 students, respectively, while the corresponding numbers in the quasi-experimental cohort were 16, 13, 10, and 15. Both cohorts followed the same curriculum and were taught by the same instructor. All collected data were anonymised prior to analysis.

3.3 Instructional Context

The study was conducted within the Synthetic Geometry II course for prospective mathematics teachers at the University of Ostrava. The course was delivered using the GTM, a technology-enhanced instructional approach integrating GeoGebra, manual geometric constructions, inquiry-based learning, and collaborative problem-solving activities. A detailed description of the model is provided in Section 2.2. The instructional activities were designed to support the development of the three components of spatial reasoning addressed in this study – mental rotation, spatial orientation, and spatial visualisation – through a sequence of progressively more complex geometry tasks. Digital technologies were used alongside traditional geometric constructions to encourage students to connect multiple representations and justify their reasoning. The assessment tasks analysed in this study were administered independently of regular course assessment and were used to examine students' spatial reasoning performance across different geometry-specific task types.

3.4 Assessment Framework

The geometry-specific assessment framework was developed as part of the broader design-based research process accompanying the iterative refinement of the GTM. The assessment tasks were designed not only to evaluate students' spatial reasoning outcomes but also to monitor their development across successive iterations of the instructional model and to provide evidence supporting its continuous refinement.

Table 1: Overview of the Geometry-Specific Assessment Framework

Test	Task ID	Task	Geometry Context	Representation(s) Involved	SR Component	Primary Cognitive Demand	Max Score
Test 1	T1.1	Cube nets	Cube nets	2D net → 3D cube	SV	Mental reconstruction of a three-dimensional object	6
	T1.2	Rolling die	Rolling cube	Dynamic 3D transformations	MR	Mental simulation of sequential rotations	30
	T1.3	Cube-net matching	Cube and net	2D ↔ 3D	SV	Matching corresponding representations	4
Test 2	T2.1	3D oblique view → Floor plan	Orthographic projections	3D → 2D	SO	Interpretation of spatial relationships from a three-dimensional representation	2
	T2.2	Floor plan → 3D oblique view	Orthographic projections	2D → 3D	SO	Mental reconstruction of a three-dimensional arrangement from a plan view	3
	T2.3	3D oblique view → Three orthographic views	Orthographic projections	3D → multiple 2D views	SO	Coordination of multiple orthographic representations	6
	T2.4	Three orthographic views → 3D oblique view	Orthographic projections	Multiple 2D views → 3D	SO	Mental reconstruction from multiple projections	3
Test 3	T3.1	Perspective viewpoint	Perspective scene	3D → viewpoint selection	SO	Perspective taking	1
	T3.2	Maze orientation	Spatial navigation	Perspective ↔ top view	SO	Mental change of viewpoint	1
	T3.3	House net	Polyhedron net	2D net → 3D object	SV	Mental reconstruction of a folded object	1
	T3.4	Prism cross-section	Cross-sections	3D object → 2D net	SV	Mental mapping of planar intersections onto a net	1
Test 4	T4.1	Odd-one-out	Block structures	3D objects	MR	Mental reflection and rotation	3
	T4.2a	Cube	Cross-sections	3D object → section	SV	Prediction of planar intersections	4

Test	Task ID	Task	Geometry Context	Representation(s) Involved	SR Component	Primary Cognitive Demand	Max Score
		cross-section					
	T4.2b	Complex cross-section	Cross-sections	3D object → section	SV	Prediction of complex planar intersections	10

In the present study, the framework is examined from a different perspective, focusing on the characteristics of individual task types and their ability to differentiate prospective mathematics teachers' spatial reasoning performance.

The assessment tasks were researcher-developed and informed by the classification principles of the Spatial Reasoning Instrument (SRI) (Ramful, Lowrie and Logan, 2017; SERC, 2022), but did not constitute a standardised administration of the SRI. Each task was classified as targeting one of the three spatial reasoning components: mental rotation (MR), spatial orientation (SO), or spatial visualisation (SV).

The assessment framework comprised four tests administered during the study, each consisting of tasks targeting one or more of these components through a range of geometric contexts, representational formats, and cognitive demands. The tasks were designed to reflect the content and reasoning processes encountered in university geometry education. An overview of the assessment framework is presented in Table 1.

The scoring procedure reflected the structure and response format of each task. Discrete response items or sub-items were scored dichotomously (0 = incorrect, 1 = correct), with scores summed when a task comprised multiple sub-items. For more complex constructed-response tasks, partial credit was awarded for predefined components or steps of a correct solution, allowing partially successful performance to be represented rather than reducing the entire response to a binary outcome (May et al, 2023). Consequently, the maximum score for each task reflected the number of scorable elements required for its complete solution.

3.5 Data Analysis

The collected data were processed using Microsoft Excel and analysed using PAST Statistics 5.0. Descriptive statistics were calculated for each assessment task and cohort. Prior to inferential analysis, data normality was assessed using the Shapiro–Wilk test. As the assumption of normality was not satisfied across the assessment tasks ($p < 0.05$), non-parametric statistical methods were applied.

Differences between the quasi-control and quasi-experimental cohorts were analysed separately for each assessment task using the Mann–Whitney U test, with the significance level set at $\alpha = 0.05$. The results are presented using descriptive statistics, boxplots, and statistical comparisons of individual assessment tasks.

4. Findings

This section presents the comparative results of the quasi-control and quasi-experimental cohorts across the four geometry-specific assessment tests. The analysis focuses on differences in performance at the task level in relation to the assessed components of spatial reasoning. Descriptive statistics are complemented by Mann–Whitney U tests to identify statistically significant differences between the cohorts. Boxplots are presented only for tasks in which statistically significant differences were identified, providing a visual representation of the score distributions.

4.1 Overall Statistical Comparison

The overall statistical results are presented in Tables 2 and 3.

Table 2: Results of the Normality and Group Comparison Tests

Test	Task ID	Normality Test Shapiro–Wilk (p)	Group Comparison <i>Mann–Whitney U</i> (p)
Test 1	T1.1	1.19E-03**	0.7319
	T1.2	8.35E-06***	0.7302
	T1.3	1.32E-03**	0.4879

Test	Task ID	Normality Test Shapiro–Wilk (p)	Group Comparison <i>Mann–Whitney U</i> (p)
Test 2	T2.1	1.85E-08***	1
	T2.2	3.20E-03**	0.0248*
	T2.3	6.54E-08***	0.0373*
	T2.4	5.61E-05***	0.0249*
Test 3	T3.1	3.54E-06***	0.2091
	T3.2	2.69E-09***	0.5369
	T3.3	1.86E-06***	Not calculated (zero variance)
	T3.4	2.89E-07***	0.0163*
Test 4	T4.1	3.48E-06***	0.1026
	T4.2a	1.13E-02*	0.2315
	T4.2b	4.99E-05***	0.9909

Statistical significance: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 3: Median Scores for the Quasi-Control and Quasi-Experimental Cohorts

Test	Task ID	Quasi-Control Group	Quasi-Experimental Group
Test 1	T1.1	0.833	0.917
	T1.2	5.500	5.500
	T1.3	0.750	0.750
Test 2	T2.1	1.000	1.000
	T2.2	2.000	1.000
	T2.3	1.000	1.000
	T2.4	2.500	0.000
Test 3	T3.1	1.000	1.000
	T3.2	1.000	1.000
	T3.3	0.000	0.000
	T3.4	1.000	0.000
Test 4	T4.1	1.000	1.000
	T4.2a	2.000	3.000
	T4.2b	2.000	2.000

Higher or equal median values are shown in **bold**.

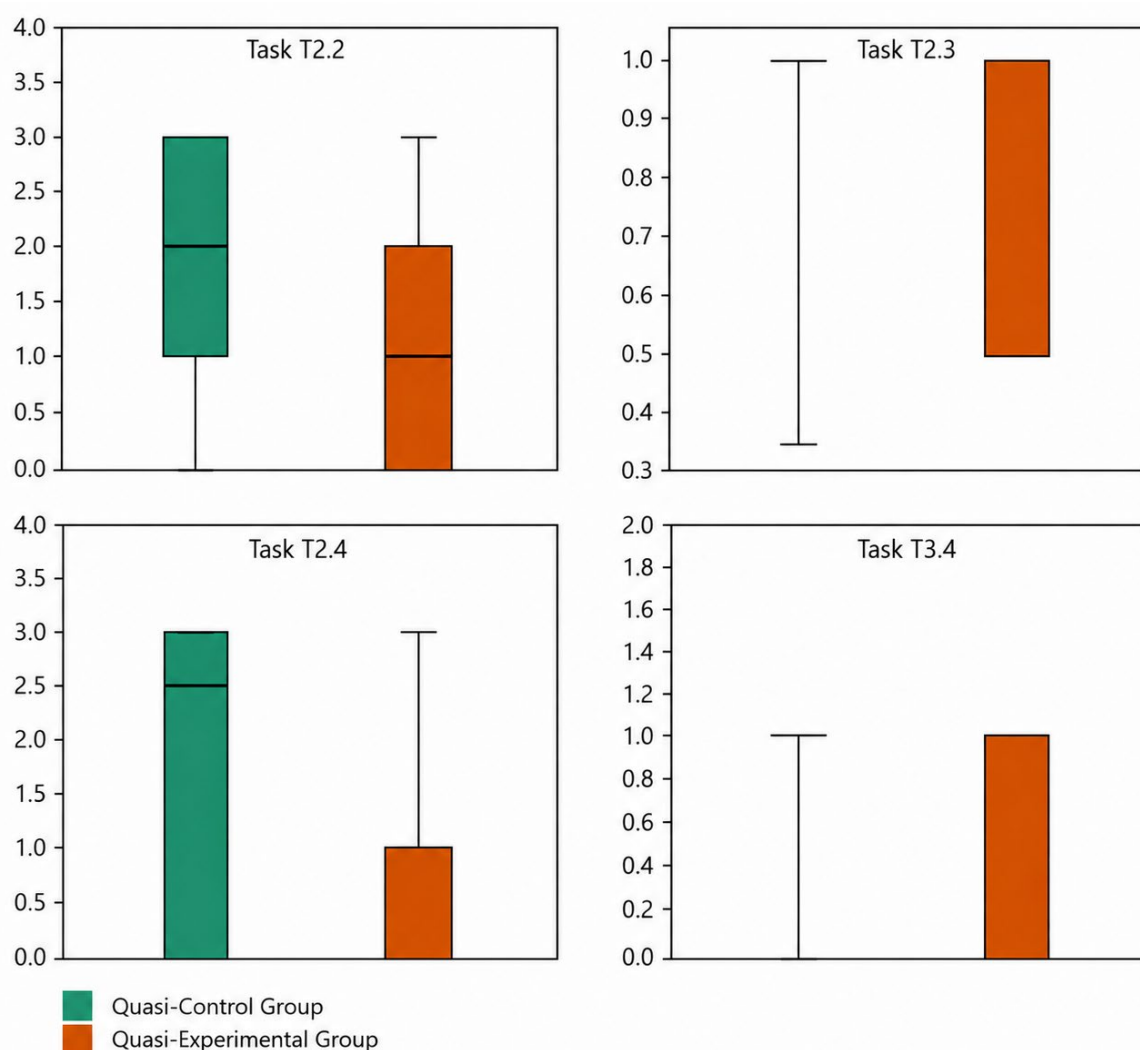


Figure 1: Boxplots of score distributions for Tasks T2.2, T2.3, T2.4, and T3.4

Table 2 summarises the results of the Mann–Whitney U tests for all assessment tasks, while Table 3 presents the corresponding median scores achieved by both cohorts. Statistically significant differences between the quasi-control and quasi-experimental cohorts were identified in four tasks: T2.2, T2.3, T2.4, and T3.4. The corresponding score distributions are presented in Figure 1.

4.2 Comparison by Assessment Test

To examine the results in more detail, the performance of the quasi-control and quasi-experimental cohorts was analysed separately for each of the four assessment tests. The following sections summarise the statistical comparisons and median scores for each assessment test, while Figure 1 presents the score distributions for the four tasks in which statistically significant differences were identified.

4.2.1 Test 1

No statistically significant differences were identified between the quasi-control and quasi-experimental cohorts in any of the three tasks included in Test 1 (Table 2). As shown in Table 3, both cohorts achieved identical median scores in Tasks T1.2 and T1.3, while only a small difference was observed in Task T1.1. Overall, the results indicate comparable performance in tasks assessing spatial visualisation and mental rotation.

4.2.2 Test 2

Among the four assessment tests, Test 2 yielded the highest number of statistically significant differences between the cohorts. No statistically significant difference was found in Task T2.1 (Table 2). In contrast,

significant differences were identified in Tasks T2.2, T2.3, and T2.4. Table 3 shows higher median scores for the quasi-control cohort in Tasks T2.2 and T2.4, whereas both cohorts achieved identical median scores in Task T2.3. The score distributions for the statistically significant tasks are presented in Figure 1.

4.2.3 Test 3

No statistically significant differences were observed in Tasks T3.1, T3.2, or T3.3 (Table 2). Table 3 shows identical median scores for both cohorts in these tasks. A statistically significant difference was identified only in Task T3.4, where the quasi-control cohort achieved a higher median score. The corresponding score distribution is presented in Figure 1.

4.2.4 Test 4

No statistically significant differences were identified between the cohorts in any of the tasks included in Test 4 (Table 2). Median scores were identical in Tasks T4.1 and T4.2b, whereas a higher median score was observed for the quasi-experimental cohort in Task T4.2a (Table 3). Despite this difference in median scores, no statistically significant difference was identified between the cohorts.

5. Discussion

The findings indicate that differences between the quasi-control and quasi-experimental cohorts were not observed across all components of spatial reasoning. Comparable performance in simpler tasks suggests that basic spatial abilities, particularly those involving mental rotation and elementary spatial orientation, may be retained over time. In contrast, statistically significant differences emerged in tasks requiring the reconstruction of three-dimensional objects from two-dimensional representations, interpretation of orthographic views, and more advanced spatial synthesis. These findings suggest that higher-order spatial reasoning abilities may be more sensitive to continuous and structured educational support than more fundamental spatial skills. This interpretation is consistent with research demonstrating that spatial abilities can be systematically developed through targeted training addressing specific spatial factors and solution strategies (Maresch, 2015).

The observed pattern of results suggests that not all components of spatial reasoning develop and are retained in the same way. The more demanding tasks required students to coordinate several cognitive processes simultaneously, including the interpretation of multiple representations, mental reconstruction of three-dimensional objects, and spatial synthesis, which is consistent with Duval's (2006) view that successful mathematical understanding depends on coordinating and converting between different semiotic representations. Such tasks place substantially higher demands on cognitive processing than isolated mental rotation or elementary orientation tasks, which may explain why differences between the cohorts became apparent only in these more complex activities.

Beyond the comparison of cohort performance, the findings also provide insights into the characteristics of geometry assessment tasks that are most effective in differentiating levels of spatial reasoning. The tasks that revealed significant differences shared common cognitive demands, including the coordination of multiple representations, interpretation of orthographic projections, and mental reconstruction of three-dimensional structures. By contrast, tasks targeting more isolated spatial processes, such as basic mental rotation or simple spatial orientation, showed limited discriminatory capacity. These findings suggest that geometry-specific assessment tasks requiring the integration of multiple spatial reasoning processes may provide a more sensitive assessment of advanced spatial competence in prospective mathematics teachers.

The findings also have implications for the design of technology-enhanced geometry learning environments in teacher education. Rather than supporting only the acquisition of basic spatial skills, such environments should provide sustained opportunities to engage with cognitively demanding tasks that require the coordination of multiple representations, dynamic visualisation, and three-dimensional reasoning. Recent research similarly indicates that technology-enhanced learning environments incorporating interactive three-dimensional visualisation tools can contribute to the development of students' spatial visualisation abilities (Medina Herrera, Juárez Ordóñez and Ruiz-Loza, 2024). The present findings suggest that technology-enhanced instruction may be particularly valuable for maintaining and strengthening these more advanced aspects of spatial reasoning. Consequently, the educational value of digital technologies depends not only on their interactive features but also on the extent to which they enable repeated engagement with cognitively demanding geometric tasks.

This study has several limitations that should be considered when interpreting the findings. The research involved students from a single teacher education programme, and the sample sizes were relatively small, which limits the generalisability of the results. The findings should therefore be interpreted as context-specific evidence rather than as representative of prospective mathematics teachers more broadly. In addition, the quasi-experimental design does not allow causal conclusions regarding the effectiveness of the instructional approach. Future research should include larger and more diverse cohorts, longitudinal designs, and further validation of geometry-specific assessment tasks to better understand the development and long-term sustainability of different components of spatial reasoning. It should also investigate whether similar patterns can be observed across different educational contexts and with alternative forms of technology-enhanced geometry instruction.

6. Conclusion

This study compared spatial reasoning outcomes between a current cohort of prospective mathematics teachers and a cohort assessed approximately one year after completing the same technology-enhanced geometry course. While both cohorts demonstrated comparable performance in simpler spatial reasoning tasks, significant differences emerged in more demanding tasks requiring the coordination of multiple representations, interpretation of orthographic views, and advanced spatial visualisation. These findings suggest that performance in higher-order spatial reasoning tasks may be particularly sensitive to the continuity of structured educational support.

Beyond the comparison of cohort performance, the study highlights the importance of carefully designed geometry assessment tasks for evaluating advanced spatial competence. Tasks requiring the integration of multiple spatial reasoning processes appear to provide more informative evidence of students' spatial thinking than tasks focusing on isolated spatial skills. The findings contribute to current research on technology-enhanced mathematics teacher education by informing the design of learning environments and assessment approaches that support the long-term development of spatial reasoning.

Ethics Declaration

Participation in the study was voluntary. All participants provided informed consent for the use of their anonymised data for research purposes, in accordance with the ethical guidelines and institutional requirements of the authors' universities for research involving human participants.

AI Declaration

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) to improve the clarity, coherence, and linguistic quality of the English text. All AI-assisted output was critically reviewed, substantially revised, and verified by the authors, who assume full responsibility for the final content of the manuscript.

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