

A Systematic Literature Review of Students' Spatial Visual Ability in Geometry Transformation Based on Student Achievement

1st Jelita Fuji Khaebibah
Mathematics Education, Swadaya
Gunung Jati University
Cirebon, Indonesia
jelita.122070009@ugj.ac.id

2nd Wahyu Hartono
Mathematics Education, Swadaya
Gunung Jati University
Cirebon, Indonesia
wahyuhartono@ugj.ac.id

3rd Tri Nopriana
Mathematics Education, Swadaya
Gunung Jati University
Cirebon, Indonesia
trinopriana@ugj.ac.id

Abstract— Visual–spatial ability represents a critical cognitive component in mathematics learning, particularly in geometric transformations, including rotation, translation, reflection, and dilation. Although previous studies have emphasized the importance of this ability, limited research has examined visual–spatial ability based on students' academic achievement levels (high, medium, and low). This study presents a systematic literature review (SLR) of 24 empirical articles published between 2020 and 2025 to examine the relationship between visual–spatial ability and learning success in geometric transformations across different achievement groups. The study selection followed the PRISMA 2020 guidelines and utilized two primary databases, namely Crossref and Google Scholar. Thematic analysis was employed to identify patterns of effective instructional strategies and variations in students' responses across achievement levels. The findings indicate that high-achieving students generally demonstrate stronger spatial capabilities that support abstract understanding of geometric concepts, whereas low-achieving students benefit more from contextualized and concrete visual approaches. These results highlight the importance of implementing differentiated pedagogical strategies that align instructional design with students' achievement profiles in order to optimize learning outcomes in geometric transformation topics.

Keywords— *spatial visualization; geometric transformation; academic achievement; mental rotation; differential pedagogy*

I. INTRODUCTION

Visual–spatial ability, defined as the capacity to mentally represent and manipulate objects in two- or three-dimensional space, has long been recognized as a strong predictor of success in mathematics learning, particularly in geometry. Visual–spatial ability refers to an individual's capacity to mentally understand, manipulate, and transform objects in two- or three-dimensional space [1]. In mathematics education, this ability plays a crucial role in understanding geometric transformations, including translation, rotation, reflection, and dilation, which involve the movement and modification of geometric shapes within the coordinate plane [2]. Students are therefore expected to mentally visualize how shapes move, rotate, or change size. However, not all students naturally possess well-developed visual–spatial abilities, and disparities in this competence may contribute to gaps in learning achievement.

Geometry is a branch of mathematics that plays a fundamental role in developing students' spatial reasoning skills [3]. Learning geometry requires students to imagine, rotate, and manipulate objects abstractly, which directly relies on visual–spatial processing [4]. Among various geometry topics, geometric transformations—including translation, rotation, reflection, and dilation—are essential concepts that require not only conceptual understanding but also strong visualization and spatial representation skills. Students must mentally simulate how shapes move, change orientation, or scale within a plane or space, making visual–spatial ability a critical cognitive component in mastering transformation concepts.

Visual–spatial ability has been identified as a key cognitive factor influencing mathematical success from an early age,

even exceeding mental rotation in predicting basic numerical skills [5]. This ability is defined as the capacity to interpret, analyze, and manipulate information in visual and spatial forms [6]. In mathematics education, visual–spatial ability has been positively correlated with academic achievement, particularly in topics requiring high levels of spatial reasoning such as geometric transformations. However, junior high school students still experience difficulties in abstract thinking when understanding and applying geometric transformations, indicating the need for more visual, contextual, and interactive learning approaches to enhance spatial understanding [7]. Recent studies also emphasize that spatial visualization is not merely a technical skill but is closely related to affective aspects such as mathematical self-concept and spatial anxiety, which directly influence mental rotation performance [8].

Several studies have demonstrated that spatial visualization skills play a crucial role in geometry learning, particularly in understanding plane and spatial shapes and solving problems based on visual representations. Students with strong spatial skills are better able to imagine, manipulate, and represent geometric objects from multiple perspectives, which is essential for solving non-routine problems [9]. Furthermore, students with high spatial visualization abilities not only perform better in geometry assessments but also employ more effective mental imagery strategies in understanding spatial transformations [7]. The use of technology-supported learning models, such as the 6E learning model assisted by GeoGebra, has also been shown to significantly improve students’ spatial visualization skills, thereby contributing to improved achievement in geometry learning [10]. These findings indicate that students with strong visualization abilities tend to understand geometric concepts more effectively and develop more efficient problem-solving strategies.

Despite its importance, visual–spatial ability does not develop evenly among students. Differences in cognitive background, learning style, prior learning experience, and affective variables such as mathematics anxiety and self-confidence influence students’ mastery of spatial visualization. Variations in academic achievement also create diversity in how students respond to geometric transformation learning. Therefore, it is important to examine how visual–spatial ability relates to student achievement levels, particularly whether high-, medium-, and low-achieving students demonstrate different patterns in developing spatial skills.

To date, most studies examining the relationship between visual–spatial ability and geometry learning have not explicitly categorized students based on achievement levels. Understanding how students with different achievement profiles respond to visual–spatial interventions may provide valuable insights for designing more effective and inclusive instructional strategies. Accordingly, this systematic literature review aims to: (1) analyze empirical evidence regarding the relationship between visual–spatial ability and achievement in geometric transformation learning; (2) identify effective instructional strategies for enhancing visual–spatial ability;

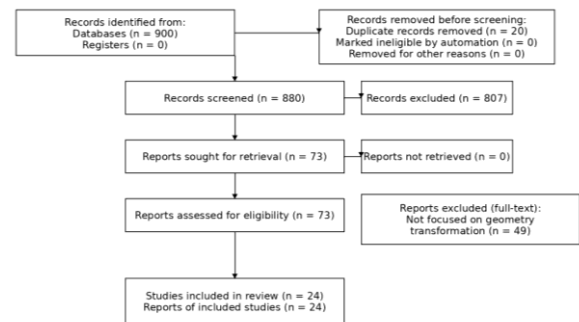
and (3) examine how different levels of academic achievement influence the outcomes of visual–spatial interventions. The findings of this study are expected to provide theoretical and practical implications for educators, curriculum designers, and researchers in developing adaptive and differentiated geometry learning approaches tailored to diverse student needs.

II. METHOD

This study employed a systematic literature review (SLR) approach following the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. Data were retrieved using the Publish or Perish software from the Crossref and Google Scholar databases, covering publications from 2020 to 2025. The search strategy utilized keywords including “spatial visualization,” “mental rotation,” “geometry transformation,” “mathematics education,” and “student achievement.”

The inclusion criteria were defined as follows: (1) empirical studies; (2) research addressing visual–spatial ability within the context of geometry education; (3) full-text availability; and (4) studies focusing on student populations. These criteria ensured that the selected articles were relevant to examining visual–spatial abilities in geometric transformation learning.

Previous studies also indicate that technology-based approaches, such as augmented reality, are effective in enhancing students’ spatial visualization and mental rotation abilities [11]. In addition, embodied cognition–based training has been shown to strengthen spatial representations through kinesthetic learning activities, thereby supporting students’ understanding of spatial transformations [12].



Picture I. PRISMA Flowchart

The initial search identified 900 articles (700 Crossref, 200 Google Scholar). After removing duplicates (n=20) and screening titles and abstracts (n=807), 73 articles were reviewed for full text. Forty-nine studies were excluded because they did not focus on geometric transformations. A total of 24 studies met the inclusion criteria and were further analyzed.

TABLE I. LIST OF 24 CORE STUDIES OF SLR GEOMETRY TRANSFORMATION AND VISUAL-SPATIAL ABILITIES

No	Year	Author	Journal Title	Journal	DOI
1	2025	Hüseyin Yalçiner & Dilay Z. Karadöller	Relationship between Spatial and Number Development: Spatial Location Knowledge Strongly Predicts Numerical Skills of Preschoolers than Mental Rotation	Research Square (Preprint)	10.21203/rs.3.rs-7636510/v1
2	2025	Bassem Khalaf	The Role Of Mental Rehearsal In Spatial And Object Imagery During Mental Rotation	Majalah Ilmu Pendidikan Jasmani	10.33984/0904-018-001-075
3	2024	AA Supli & X Yan	The effectiveness of augmented reality in enhancing spatial reasoning skills	Education and Information Technologies	10.1007/s10639-023-12255-w
4	2024	J Yu & AR Denham	Utilizing augmented reality for embodied mental rotation training	British Journal of Educational Technology	10.1111/bjet.13397
5	2024	Michelle Lennon-Maslin et al.	Beyond numbers: the role of mathematics self-concept and spatial anxiety in shaping mental rotation performance	Frontiers in Education	10.3389/educ.2024.1300598
6	2024	DF Ali et al.	Enhancing Student's 3D Development and Mental Rotation Skill Using Augmented Reality	International Journal of Academic Research	10.6007/IJAR PED/v13-i3/21966
7	2024	Michelle Lennon-Maslin & Claudia Quaiser-Pohl	Mindset Matters: The Role of Mathematics Self-concept and Age in Mental Rotation Performance	Lecture Notes in Computer Science	10.1007/978-3-031-63115-3_2
8	2023	M Rahe & C Quaiser-Pohl	Can perceived mental-rotation performance mediate gender differences in math anxiety	Mathematics Education Research Journal	10.1007/s13394-021-00387-6
9	2022	PD Diago et al.	Exploring the development of mental rotation and computational skills through educational	International Journal of Child-Computer Interaction	https://doi.org/10.1016/j.ijcci.2021.100388

10	2022	L Arrighi & M Hausmann	robotics Spatial anxiety and self-confidence mediate sex/gender differences in mental rotation	Learning & Memory	10.1101/m.053596.122
11	2022	Y Zhou et al.	Improving spatial visualization and mental rotation using FORSpatial	IEEE Transactions on Learning Technologies	10.1109/TLT.2022.3170928
12	2022	Linda Arrighi & Markus Hausmann	Spatial anxiety and self-confidence mediate sex/gender differences in mental rotation	Learning & Memory	10.1101/m.053596.122
13	2022	Yun Zhou et al.	Improving Spatial Visualization and Mental Rotation Using FORSpatial	IEEE Transactions on Learning Technologies	10.1109/tlt.2022.3170928
14	2021	Eylül Turan et al.	Spatial language and mental transformation in preschoolers	Cognitive Development	10.1016/j.cogdev.2020.100980
15	2021	S Ariali & B Zinn	Adaptive training of the mental rotation ability in an immersive virtual environment	Journal of Emerging Technologies in Learning	https://doi.org/10.3991/ijet.v16i09.18971
16	2021	Jing Lin	Modeling the Relations Between Self-Efficacy, Interest, Spatial Visualization, and Mental Rotation in STEM Education	AERA Annual Meeting	10.3102/1682053
17	2021	S M S Syquia	Recognizing mental rotation and spatial visualization skills in Minecraft	Proceedings of the International Conference on Future of Education	10.17501/26307413.2021.4105
18	2021	Atara Shriki & Dorit Patkin	Developing Spatial Skills through Mental Rotation Activities	Mathematics Teacher: Learning and Teaching PK-12	10.5951/mtl.2020.0267
19	2021	Hi-Lian Jeng & Yi-Lung Lin	Effect of Time Constraint in Exploring Spatial Differences	Frontiers in Education	10.3389/educ.2021.712691
20	2020	IE Lokka &	Perspective	Cartogra	10.108

		A Çöltekin	switch and spatial knowledge acquisition	phy and Geographic Information Science	0/1523 0406.2 019.15 95151
21	2020	HE Dere & F Kalelioglu	The effects of using web-based 3D design environment on spatial visualisation	Informatics in Education	10.15388/infe du.2020 0.18
22	2020	H. Ebru Dere & Filiz Kalelioglu	Web-Based 3D Design Environment on Spatial Visualisation	Informatics in Education	10.15388/infe du.2020 0.18
23	2020	Yvonne K. Ralph et al.	Gender differences in mothers' spatial language use and children's mental rotation abilities	Developmental Science	10.1111/desc. 13037
24	2020	S Ariali	Training of mental rotation ability in virtual spaces	Journal of Technical Education (JOTED)	https://doi.org/10.48513/joted.v8i2.207

		Factors in a Redrawn Mental Rotation Test		
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III. RESULTS AND DISCUSSION

The findings of this study indicate that students with high spatial visualization abilities demonstrate greater efficiency in completing geometric transformation tasks, including rotation, reflection, and translation. These students are able to construct accurate mental representations of objects and manipulate them to understand positional and structural changes. In contrast, students with lower spatial abilities tend to experience difficulties in maintaining stable visual representations, which may lead to conceptual and procedural errors in geometric interpretation. These findings are consistent with previous research [13], which identified mathematical self-concept and spatial anxiety as significant determinants of mental rotation performance, with individuals possessing positive self-concepts demonstrating higher spatial efficiency. Similarly, study [14] reported that perceived spatial ability functions as an important mediating factor between gender and mathematics anxiety. Furthermore, [15] indicated that time constraints influence students who rely on slower visualization strategies, whereas those employing segmented spatial strategies tend to adapt more effectively to time pressure.

Furthermore, this study provides a comprehensive framework for understanding the factors contributing to variations in students' spatial performance without explicitly categorizing learners based on achievement levels. It highlights the roles of variables such as mathematical self-concept, spatial anxiety, perceived ability, and learning environment conditions. These factors offer an important foundation for designing adaptive pedagogical interventions that accommodate diverse psychological characteristics and cognitive strategies among learners.

TABLE II. CHARACTERISTICS OF STUDIES THAT HIGHLIGHT PSYCHOLOGICAL ASPECTS OF SPATIAL PERFORMANCE

No	Year	Title	Source	DOI
1	2024	Beyond numbers: the role of mathematics self-concept and spatial anxiety in shaping mental rotation performance and STEM preferences in primary education	Frontiers in Education	10.3389/feduc.2024.1300598
2	2024	Mindset Matters: The Role of Mathematics Self-concept and Age in Mental Rotation Performance Among Primary School Children	Lecture Notes in Computer Science	10.1007/978-3-031-63115-3_2
3	2023	Can (perceived) mental-rotation performance mediate gender differences in math anxiety in adolescents and young adults?	Mathematics Education Research Journal	10.1007/s13394-021-00387-6
4	2021	Effect of Time Constraint in Exploring Spatial Differences With Balanced Allocation of Performance	Frontiers in Education	10.3389/feduc.2021.712691

Beyond cognitive and affective factors, technological integration has emerged as an important element in the development of spatial abilities. Studies [11] and [12] demonstrate that augmented reality in geometry learning provides significant benefits for spatial visualization and the manipulation of three-dimensional objects. Technology-based visualization enables multisensory learning experiences, thereby strengthening visual and spatial representations. These findings are further supported by research [16], which introduced the FORSpatial platform for mental visualization training and reported significant improvements in students' spatial precision. Gender differences also remain an important consideration, as findings from [17] indicate that spatial anxiety and self-confidence contribute to gender-related differences in mental rotation performance. Therefore, spatial learning approaches that incorporate affective and psychosocial dimensions are highly relevant for implementation in inclusive and adaptive classroom environments.

Studies on early linguistic interaction further suggest that spatial abilities can be developed from an early age. Research [18] and [19] reported that the use of spatial language by parents and teachers is significantly associated with early mental representation and spatial rotation abilities in children. Exposure to spatial terminology and verbal discussions about position, direction, and shape provides an important foundation for the development of geometric reasoning. Additionally, research [20] expanded the affective and developmental perspective in spatial performance,

emphasizing that age and the development of mathematical self-concept are associated with reduced pressure in completing mental rotation tasks. The study also indicated that increasing age does not necessarily guarantee improved performance, but is often accompanied by stabilized self-concept and reduced anxiety, which contribute to enhanced cognitive efficiency in spatial processing.

Overall, these findings confirm that spatial visualization plays a central role in geometric transformation performance while also highlighting the importance of affective factors, instructional strategies, and technology-supported learning environments as key determinants of students' success in

Achievement Level	Effective Strategies	Example Media	Response Characteristics
High	Exploration and independent tasks	GeoGebra, Virtual Reality (VR)	Quickly understands abstract concepts
Medium	Gradual visualization, collaborative work	Simple Augmented Reality (AR), animation	Requires structured guidance, shows strong engagement
Low	Contextual and manipulative learning	Physical 3D models, concrete videos	Needs guidance, repetition, and intensive support

visual geometry tasks.

1. Pattern of Relationship between Spatial Visualization and Achievement

All core studies demonstrated a significant positive relationship between spatial visualization, particularly mental rotation ability, and achievement in geometric transformation tasks. Technology-supported interventions, including augmented reality, embodied training, and virtual learning environments such as GeoGebra and Minecraft Education Edition, showed the most substantial impact on improving students' spatial visualization skills. These approaches enable interactive and multisensory learning experiences that strengthen students' ability to mentally manipulate geometric objects and understand transformation processes.

Studies examining the use of augmented reality (AR), virtual reality (VR), and game-based learning environments consistently reported significant improvements in students' spatial abilities. These findings highlight the importance of mental rotation training through interactive media to deepen students' understanding of geometric transformations. Moreover, positive mathematical mindsets and self-efficacy have been shown to further enhance success in spatial rotation tasks, as reported by [20]. In many cases, technology-based spatial visualization development not only improves students' performance but also helps bridge the understanding gap between high- and low-achieving learners.

2. Responses Based on Achievement Level

The analysis indicates that students with different achievement levels demonstrate distinct responses to spatial visualization interventions. High-achieving students tend to respond positively to exploratory learning and challenge-based tasks. They are better able to utilize simulated environments and mathematical abstractions to solve transformation problems efficiently.

Students with medium achievement levels show significant improvement when provided with gradual and structured visual support. Collaborative learning approaches, along with the use of instructional media such as simple augmented reality animations, appear to be particularly effective for this group. These strategies help scaffold spatial reasoning while maintaining engagement in transformation tasks.

In contrast, low-achieving students require more concrete and contextual learning strategies. The use of manipulative media, including physical three-dimensional models, instructional videos, and explicit step-by-step guidance, is necessary to support their understanding of geometric transformations. Such approaches help students gradually construct stable visual representations and reduce conceptual difficulties in spatial reasoning.

TABLE III. COMPARISON OF INTERVENTION STRATEGIES BASED ON ACHIEVEMENT LEVEL

3. Literature Limitations and Future Directions

Although this review includes 24 empirical studies from diverse educational contexts and methodological approaches, several limitations should be acknowledged. First, most of the included studies were conducted in developed country contexts, which limits the generalizability of the findings to educational settings in developing countries such as Indonesia. Therefore, caution is required when applying these results to different sociocultural and educational environments.

Second, only a limited number of studies explicitly differentiated outcomes based on achievement-level segmentation (high, medium, and low). As a result, interpretations regarding differences among achievement groups are often inferential rather than directly evidenced. Third, affective dimensions—such as spatial anxiety, mathematical self-concept, and interest in STEM—have not been comprehensively integrated into the design of spatial learning interventions.

Future research should adopt mixed-method approaches that combine quantitative and qualitative data to examine cognitive and affective factors simultaneously. Longitudinal studies are also recommended to investigate the development of visual-spatial abilities over time and to evaluate the long-term effects of technology-based interventions, including augmented reality and virtual reality, on students' spatial reasoning performance.

4. Implications and Recommendations of the Study Results

The findings of this study provide several practical implications for educators, curriculum designers, and mathematics education researchers. First, instructional interventions in geometric transformation learning should be tailored to students' visual-spatial ability profiles. Students with lower spatial abilities benefit more from concrete manipulatives and guided visualization, whereas students with higher spatial abilities can be challenged through digital simulations such as GeoGebra and virtual reality environments.

Second, practical diagnostic tools should be developed at the school level to identify students' spatial profiles at an early stage. Such assessments would enable teachers to design differentiated instructional strategies that better accommodate diverse learning needs. Third, teacher training in the use of interactive visual media should become an integral component of professional development programs in mathematics education.

Furthermore, future curriculum development should not only emphasize conceptual understanding of geometry but also explicitly integrate mental rotation training and spatial visualization activities. The incorporation of adaptive augmented reality-based educational technologies, as highlighted in previous studies [11], [12], offers a strategic opportunity to reduce disparities in students' spatial achievement and enhance learning outcomes in geometric transformation

IV. CONCLUSIONS

Visual-spatial ability represents a critical cognitive component in learning geometric transformations. The findings of this study indicate that the effectiveness of visual learning strategies is significantly influenced by students' achievement levels. Accordingly, instructional interventions should be tailored to the characteristics of each achievement group. High-achieving students benefit more from exploratory and simulation-based approaches, whereas medium- and low-achieving students require structured and concrete visual support to facilitate conceptual understanding. In this context, differentiated instructional strategies based on visual simulations, including virtual reality and augmented reality, are highly relevant for reducing disparities in students' spatial abilities [21], [22].

The results of this systematic literature review further suggest that the integration of spatial visualization technologies—such as augmented reality, virtual reality, and manipulative media—can significantly enhance students' understanding of geometric transformation concepts. However, these technological approaches should be contextualized and combined with adaptive pedagogical strategies to achieve optimal effectiveness. Additionally, the development of diagnostic tools capable of accurately classifying students according to achievement levels is essential for designing more targeted interventions.

Future research should employ mixed-method approaches to explore both cognitive and affective dimensions influencing visual-spatial ability, particularly within the Indonesian educational context. Overall, this study provides both theoretical and practical contributions to understanding visual-spatial ability and its implications for geometry learning, while supporting the development of more inclusive, contextual, and needs-based instructional practices.

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