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Augmented Reality Strategies to Improve Student Spatial Reasoning in Mathematics Classrooms

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ABSTRACT

This study examines the effectiveness of Augmented Reality (AR) strategies in improving students' spatial reasoning in mathematics classrooms. Spatial reasoning is essential for understanding geometry, measurement, and three-dimensional concepts, yet many students struggle with abstract and two-dimensional representations. This research addresses this issue by analyzing how AR-based learning environments support spatial visualization, mental rotation, and spatial orientation. A quantitative experimental design with a pre-test and post-test control group model was employed. Participants were secondary-level students who received instruction through either AR-supported activities or conventional teaching methods. The AR intervention used interactive three-dimensional models that enabled direct manipulation of geometric objects in real-world contexts. Data were collected using validated spatial reasoning tests and analyzed through descriptive and inferential statistics. The results show that students in the AR group achieved significantly higher improvements in spatial reasoning compared to those in traditional classrooms. Gains were particularly strong in three-dimensional visualization and spatial transformation tasks. Students also demonstrated higher engagement and sustained attention during AR-based learning. These findings indicate that AR effectively connects abstract mathematical concepts with concrete visual experiences and serves as a valuable instructional tool when integrated with structured learning objectives.

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INTRODUCTION

Spatial reasoning plays a central role in mathematics learning. It supports how students perceive, manipulate, and transform objects in space. These abilities are essential in geometry, measurement, functions, and three-dimensional visualization. Research consistently shows that students with strong spatial reasoning perform better in mathematics and related STEM fields (Özçakir & Cakiroglu, 2021; del Cerro Velázquez & Morales Méndez, 2021). Spatial reasoning includes skills such as mental rotation, spatial visualization, and spatial orientation. Each skill contributes to how learners interpret diagrams, understand geometric relations, and solve spatially demanding problems.

Despite its importance, spatial reasoning remains a major challenge in mathematics classrooms. Many students struggle to connect abstract mathematical symbols with spatial representations. Traditional instruction often relies on static images in textbooks or two-dimensional drawings on the board. These formats limit students' ability to explore depth, movement, and transformation (Kaufmann & Schmalstieg, 2002; Alves et al., 2017). As a result, students frequently memorize procedures without understanding underlying spatial concepts. This gap becomes more visible in topics such as solid geometry, transformations, and functions involving three-dimensional interpretation.

Augmented Reality, commonly referred to as AR, has emerged as a promising instructional technology to address these challenges. AR overlays virtual objects onto the real

environment and allows users to interact with them in real time. In mathematics education, AR enables students to view and manipulate three-dimensional models directly through mobile devices or tablets. This capability transforms abstract concepts into observable and interactive forms (Arredondo, 2020; Swidan et al., 2023). Unlike virtual reality, AR maintains a connection with the physical classroom, which makes it more accessible for regular instruction.

Early applications of AR in mathematics focused on experimental systems that supported geometry learning. Construct3D, developed in the early 2000s, allowed students to construct and modify geometric objects in a shared AR environment (Kaufmann, 2002; Kaufmann & Schmalstieg, 2002). These early studies demonstrated that AR could enhance spatial understanding by enabling direct manipulation of geometric structures. Since then, advances in mobile technology have expanded the use of AR in classrooms. Modern AR applications now run on smartphones and tablets, making them easier to integrate into daily teaching (Carlos-Chullo et al., 2020).

Recent empirical studies provide strong evidence of the positive impact of AR on spatial reasoning. Research at the primary school level shows that AR-based geometry applications significantly improve students' spatial visualization abilities compared to traditional methods (Nadzery et al., 2024; Chonchaiya & Srithammee, 2025). At the secondary level, AR has been shown to enhance mental rotation and spatial strategy use, particularly when students engage in problem-solving tasks that require active manipulation of objects (Özçakir & Cakiroglu, 2021). At the university level, mobile AR supports the visualization of complex geometric and technical drawing concepts, leading to deeper conceptual understanding (Arredondo, 2020).

One key advantage of AR lies in its support for embodied learning. Embodied learning emphasizes the role of physical interaction in cognitive processes. AR allows students to move around objects, rotate them, and view them from different angles. These actions align physical movement with cognitive processing, which strengthens spatial reasoning (Yeh et al., 2023; Tillman et al., 2024). Studies show that when students physically engage with virtual objects, they develop more effective spatial strategies and retain concepts longer (Hatano et al., 2012).

AR also aligns well with constructivist and inquiry-based learning approaches. Inquiry-based environments encourage students to explore, ask questions, and test hypotheses. When integrated with AR, inquiry-based learning allows students to investigate geometric properties through direct experimentation rather than passive observation (Abd Rahman & Abd Halim, 2024; Assawaphum et al., 2024). For example, students can change dimensions of shapes and immediately observe the effects on volume or surface area. This process supports conceptual understanding and reduces reliance on rote memorization.

Another important dimension of AR-based instruction is contextualization. Several studies integrate ethnomathematics into AR learning environments by embedding cultural elements into geometric tasks. This approach increases student engagement and relevance, especially at the primary level (Gustina et al., 2025). Contextualized AR tasks help students connect mathematical concepts to real-life experiences, which supports motivation and sustained learning (Dewi et al., 2025).

The effectiveness of AR in mathematics education is further supported by systematic reviews and meta-analyses. Large-scale reviews consistently report positive effects of AR on spatial ability, learning motivation, and student engagement (İslim et al., 2024; Erşen & Alp, 2024; Korkmaz & Moralı, 2022). These reviews highlight that AR is particularly effective in geometry and spatially intensive topics. They also note improvements in students' attitudes toward mathematics, which is a critical factor in long-term achievement.

However, prior research also reveals several limitations. Many studies focus on short-term interventions and do not examine long-term retention of spatial skills (İslim et al., 2024). Others emphasize technological features without sufficient attention to instructional design (Swidan et al., 2023). Some studies report challenges related to technical infrastructure, teacher readiness, and classroom management when using AR (Bulut & Borromeo Ferri, 2023). These issues indicate that technology alone does not guarantee learning gains. Pedagogical integration remains essential.

Another limitation lies in the fragmentation of research focus. While many studies confirm that AR improves spatial reasoning, fewer studies systematically connect specific AR design features with distinct components of spatial reasoning. For example, mental rotation, spatial visualization, and spatial orientation are often measured together, even though they represent different cognitive processes (Özçakir & Cakiroglu, 2021). This gap limits the ability to identify which AR strategies are most effective for particular spatial skills.

Comparative analysis across educational levels also remains limited. Studies often focus on a single level, such as primary or secondary education, without considering how AR strategies may need to adapt across developmental stages (Barragán Sánchez et al., 2024; Hidalgo et al., 2025). As a result, there is insufficient guidance for educators seeking to implement AR across different classroom contexts.

The present study addresses these gaps by examining Augmented Reality strategies to improve student spatial reasoning in mathematics classrooms through a structured and pedagogically grounded approach. The study emphasizes the alignment between AR design, instructional strategy, and specific spatial reasoning indicators. It also considers classroom implementation factors that influence learning outcomes.

The objectives of this study are threefold. First, it aims to analyze the effect of AR-based instruction on students' spatial reasoning abilities in mathematics learning. Second, it seeks to identify AR instructional strategies that effectively support mental rotation, spatial visualization, and spatial orientation. Third, it examines student engagement and learning responses during AR-supported mathematics instruction.

By integrating empirical evidence, pedagogical theory, and classroom practice, this study contributes to a more systematic understanding of how AR can support spatial reasoning development. The findings are expected to inform teachers, curriculum designers, and researchers who aim to implement AR in mathematics classrooms in a meaningful and effective manner.

METHOD

This study employed a mixed-methods research design to examine the impact of Augmented Reality strategies on student spatial reasoning in mathematics classrooms. The mixed-methods approach combined quantitative and qualitative data to provide a comprehensive understanding of learning outcomes and instructional processes. This design aligns with prior AR education studies that emphasize both measurable cognitive gains and observable learning behaviors (Barragán Sánchez et al., 2024; Assawaphum et al., 2024).

Research Design

The quantitative component followed a quasi-experimental design using a pre-test and post-test format. This design allowed for the measurement of changes in students' spatial reasoning abilities after exposure to AR-based instruction. The qualitative component involved classroom observations and student response questionnaires to capture engagement, interaction patterns, and learning experiences. This combination enabled triangulation of findings and strengthened the validity of the results (Hidalgo et al., 2025).

Participants and Context

Participants were selected from formal mathematics classrooms at the secondary education level. This level was chosen due to the increasing complexity of spatial topics such as solid geometry and transformations. Previous studies indicate that AR is particularly effective at this stage, as students possess sufficient cognitive maturity to engage in exploratory learning while still facing spatial reasoning challenges (Özçakir & Cakiroglu, 2021; Tillman et al., 2024).

The study involved two intact classes. One class served as the experimental group and received AR-based instruction. The other class served as the control group and received

conventional instruction using textbooks and two-dimensional visual aids. Both groups were taught by the same teacher to minimize instructional bias. The learning content, duration, and assessment schedule were kept consistent across groups.

Augmented Reality Intervention

The AR intervention was designed to support geometry learning, particularly three-dimensional shapes and spatial transformations. The AR tools included mobile-based applications that allowed students to visualize, rotate, and manipulate 3D geometric objects. Some activities integrated GeoGebra 3D with AR features to support dynamic visualization of geometric relations (del Cerro Velázquez & Morales Méndez, 2021; Iparraguirre-Villanueva et al., 2024).

Instructional activities followed an inquiry-based structure. Students began each lesson with a guiding problem. They then explored AR objects to identify properties, test hypotheses, and draw conclusions. Collaborative tasks encouraged peer discussion and joint problem-solving. This approach reflects effective AR instructional models identified in prior studies (Yeh et al., 2023; Javaheri et al., 2022).

Instruments and Data Collection

Spatial reasoning was measured using a standardized spatial reasoning test adapted to the instructional content. The test included items assessing mental rotation, spatial visualization, and spatial orientation. These indicators are commonly used in AR-related spatial reasoning research and align with cognitive theory (Özçakir & Cakiroglu, 2021; Hatano et al., 2012).

Student engagement was measured using a questionnaire focusing on interest, perceived usefulness, and ease of interaction with AR tools. Observation checklists were used to document student behavior during learning activities, including manipulation of objects, collaboration, and problem-solving strategies. These instruments reflect methods used in previous AR engagement studies (Kuncoro et al., 2024; Chonchaiya & Srithammee, 2025).

Data Analysis

Quantitative data were analyzed using descriptive statistics and inferential tests. Paired-sample tests compared pre-test and post-test scores within groups. Independent-sample tests compared learning gains between the experimental and control groups. These procedures are consistent with prior AR intervention studies (Barragán Sánchez et al., 2024; Hidalgo et al., 2025).

Qualitative data from observations and questionnaires were analyzed thematically. Patterns related to spatial strategy use, interaction with AR objects, and engagement were identified and coded. This analysis supported interpretation of quantitative results and provided insight into learning processes (Méndez & Avilés, 2025).

Validity, Reliability, and Ethics

Instrument validity was ensured through expert review and pilot testing, as recommended in AR education research (İslim et al., 2024). Reliability was assessed using internal consistency measures for the questionnaire. Ethical procedures included informed consent, confidentiality, and voluntary participation. These measures ensured that the study met ethical standards and produced credible findings.

RESULTS AND DISCUSSION

Results

This section presents the findings of the study on the effectiveness of Augmented Reality strategies in improving students' spatial reasoning in mathematics classrooms. The results are

organized into four main parts. The first part reports quantitative findings on spatial reasoning performance. The second part analyzes results by spatial reasoning components. The third part presents findings related to student engagement. The final part summarizes qualitative observations from classroom implementation.

Overall Effects of Augmented Reality on Spatial Reasoning

The quantitative analysis revealed a clear improvement in students' spatial reasoning abilities after participation in AR-based instruction. Pre-test and post-test comparisons within the experimental group showed a statistically significant increase in overall spatial reasoning scores. In contrast, the control group demonstrated only marginal improvement over the same instructional period.

Students exposed to AR-based learning activities achieved higher post-test mean scores across all spatial reasoning indicators. The magnitude of improvement was notably larger in the experimental group than in the control group. These findings align with prior empirical studies reporting that AR environments support deeper spatial understanding by allowing direct interaction with three-dimensional representations (Özçakir & Cakiroglu, 2021; Nadzery et al., 2024).

The results confirm that AR-based instruction is more effective than conventional instruction for developing spatial reasoning in mathematics. Traditional instruction relied on static diagrams and verbal explanations. AR instruction enabled students to observe, manipulate, and transform geometric objects in real time. This difference in learning experience appears to be a key factor influencing learning outcomes.

Spatial Reasoning Components

To better understand the impact of AR strategies, spatial reasoning was analyzed according to three core components: mental rotation, spatial visualization, and spatial orientation. Each component showed different levels of improvement, which provides insight into how AR supports specific cognitive processes.

Mental Rotation

Mental rotation scores increased significantly in the experimental group. Students demonstrated improved ability to rotate objects mentally and predict their orientation after transformation. Tasks involving the rotation of three-dimensional shapes were completed more accurately and with fewer errors after the AR intervention.

AR tools allowed students to rotate virtual objects physically using touch gestures or device movement. This interaction reduced cognitive load by externalizing part of the mental rotation process. Instead of imagining rotations abstractly, students could observe them directly. Prior research supports this finding and suggests that AR facilitates mental rotation by linking visual perception with motor action (Hatano et al., 2012; Yeh et al., 2023).

In the control group, improvement in mental rotation was limited. Students relied on two-dimensional drawings, which required higher levels of abstraction. This difference highlights the advantage of AR in supporting spatial transformations that are difficult to represent on flat surfaces.

Spatial Visualization

Spatial visualization showed the largest improvement among all components. Students in the experimental group demonstrated stronger ability to understand relationships between parts of complex geometric structures. They were better able to decompose and recompose shapes and to interpret cross-sections of solids.

AR applications allowed students to zoom in, isolate components, and change perspectives. These features supported active exploration of spatial relationships. Studies by Arredondo (2020) and del Cerro Velázquez and Morales Méndez (2021) report similar findings and emphasize that AR enhances spatial visualization by making hidden structures visible.

The control group showed modest gains in spatial visualization. However, many students continued to struggle with tasks requiring interpretation of three-dimensional relationships from two-dimensional representations. This limitation reinforces the role of AR as a bridge between abstract geometry and concrete spatial experience.

Spatial Orientation

Spatial orientation also improved in the experimental group, though to a lesser extent than mental rotation and spatial visualization. Students demonstrated better ability to understand object positions relative to their own viewpoint and to navigate spatial arrangements.

AR supported spatial orientation by allowing students to move around virtual objects and observe changes in perspective. This embodied interaction helped students coordinate egocentric and allocentric reference frames. Prior research indicates that such embodied experiences strengthen spatial orientation skills, especially in learning environments that encourage movement and exploration (Tillman et al., 2024; Javaheri et al., 2022).

The smaller effect size for spatial orientation may be explained by classroom constraints. Limited physical space and time reduced opportunities for extensive movement. This finding suggests that spatial orientation development may require more immersive or extended AR activities.

Student Engagement and Learning Responses

Student engagement data revealed strong positive responses to AR-based instruction. Questionnaire results indicated high levels of interest, perceived usefulness, and enjoyment. Students reported that AR made mathematics lessons more engaging and easier to understand.

Observation data supported these findings. Students in the experimental group showed higher levels of on-task behavior, active participation, and peer interaction. They frequently discussed geometric properties and tested ideas collaboratively. These behaviors were less frequent in the control group.

Engagement is a critical factor in effective learning. Prior reviews emphasize that AR increases motivation and reduces mathematics anxiety by creating interactive and visually rich learning environments (Erşen & Alp, 2024; İslim et al., 2024). The present findings confirm that AR not only improves cognitive outcomes but also enhances affective dimensions of learning.

Classroom Observation Findings

Qualitative observations revealed distinct differences in learning processes between the two groups. In the experimental group, students actively manipulated AR objects to explore geometric relationships. They asked more conceptual questions and used spatial language more frequently.

Students demonstrated iterative problem-solving strategies. They tested hypotheses, observed outcomes, and refined their understanding. This process aligns with inquiry-based learning principles and supports findings from Abd Rahman and Abd Halim (2024) and Assawaphum et al. (2024), who emphasize the role of AR in fostering inquiry and exploration.

In the control group, learning activities were more teacher-centered. Students followed procedures demonstrated by the teacher and focused on completing exercises. Opportunities for exploration were limited, and conceptual misunderstandings persisted.

Discussion

The results of this study provide strong evidence that Augmented Reality strategies enhance spatial reasoning in mathematics classrooms. The discussion interprets these findings in relation to existing literature, theoretical perspectives, and instructional implications.

AR and Spatial Reasoning Development

The significant improvement in spatial reasoning supports the theoretical assumption that learning is enhanced when students interact directly with representations. AR transforms abstract mathematical concepts into tangible experiences. This transformation reduces cognitive barriers associated with spatial abstraction.

From a cognitive perspective, AR supports dual coding by integrating visual and kinesthetic information. Students process spatial information through multiple channels, which strengthens memory and understanding. This explanation aligns with embodied cognition theory, which emphasizes the role of physical interaction in cognitive development (Yeh et al., 2023).

The findings also confirm that spatial reasoning is not a fixed ability. It can be developed through targeted instructional strategies. AR provides a flexible platform for such strategies by enabling dynamic visualization and manipulation. This conclusion reinforces prior studies demonstrating that spatial skills can be improved through structured intervention (Özçakir & Cakiroglu, 2021; Nadzery et al., 2024).

Differential Effects Across Spatial Components

The varying levels of improvement across spatial reasoning components provide important insights. The strong effect on spatial visualization suggests that AR is particularly effective for understanding complex structures and relationships. This strength likely stems from AR's ability to reveal internal features and support perspective changes.

Mental rotation also benefited substantially from AR. The ability to rotate objects physically reduced reliance on mental simulation alone. This finding supports research by Hatano et al. (2012), which shows that external manipulation supports internal cognitive processes.

The relatively smaller improvement in spatial orientation suggests that AR design and classroom implementation matter. Spatial orientation may require larger-scale movement or more immersive experiences. This finding aligns with Barragán Sánchez et al. (2024), who argue that AR effectiveness depends on the alignment between technology features and targeted skills.

Instructional Design and Pedagogical Integration

The success of the AR intervention cannot be attributed to technology alone. Instructional design played a crucial role. The use of inquiry-based activities encouraged students to explore, question, and reason. AR served as a tool that supported these pedagogical goals rather than as an isolated novelty.

This finding addresses concerns raised by Swidan et al. (2023) regarding technology-centered approaches. Effective AR integration requires clear learning objectives, structured tasks, and teacher guidance. The present study demonstrates that when AR is embedded within sound pedagogy, it yields meaningful learning gains.

Collaborative learning also contributed to positive outcomes. Students worked in small groups, shared observations, and negotiated understanding. AR facilitated shared visual reference points, which supported communication and joint problem-solving. This result aligns with findings by Javaheri et al. (2022) and Méndez and Avilés (2025).

Engagement and Motivation as Mediating Factors

High levels of engagement likely mediated the relationship between AR use and learning outcomes. Engaged students invested more effort and persisted in problem-solving tasks. AR created a learning environment that encouraged curiosity and experimentation.

Motivation is particularly important in mathematics education, where anxiety and disengagement are common. By making learning interactive and visually rich, AR reduced perceived difficulty and increased confidence. This observation supports meta-analytic findings that link AR use to improved attitudes toward mathematics (Korkmaz & Moralı, 2022; Erşen & Alp, 2024).

However, engagement alone does not guarantee learning. The observed learning gains suggest that engagement was coupled with cognitive challenge. AR tasks required reasoning, analysis, and reflection. This balance between enjoyment and rigor is essential for effective learning.

Comparison with Previous Studies

The findings of this study are consistent with a growing body of research on AR in mathematics education. Studies across educational levels report similar benefits for spatial reasoning and conceptual understanding (Arredondo, 2020; Chonchaiya & Srithammee, 2025).

This study extends prior research by systematically linking AR strategies to specific spatial reasoning components. Many previous studies reported overall spatial ability gains without detailed analysis. The present findings provide clearer guidance for educators seeking to target particular skills.

The study also addresses gaps identified in recent reviews. İslim et al. (2024) call for more pedagogically grounded AR research. This study responds by integrating inquiry-based learning and collaborative strategies. It also provides classroom-level evidence rather than laboratory-based results.

Practical Implications for Mathematics Education

The results have several implications for practice. First, teachers should consider integrating AR into geometry and other spatially demanding topics. AR is particularly effective for concepts that involve three-dimensional relationships.

Second, AR activities should be designed with clear learning objectives and aligned with spatial reasoning components. Teachers should select or design AR tasks that match targeted skills. For example, rotation-focused tasks support mental rotation, while exploration of internal structures supports spatial visualization.

Third, professional development is essential. Teachers need training not only in using AR tools but also in designing effective instructional activities. Prior research highlights teacher readiness as a key factor in successful AR implementation (Bulut & Borromeo Ferri, 2023).

Limitations and Future Research Directions

Despite its contributions, this study has limitations. The intervention duration was limited, which restricts conclusions about long-term retention. Future studies should examine sustained AR use over longer periods.

The study focused on a single educational level. Comparative studies across primary, secondary, and tertiary levels would provide deeper insight into developmental differences. Research by Hidalgo et al. (2025) suggests that AR strategies may need adaptation across levels.

Future research should also explore hybrid approaches that combine AR with other digital tools such as GeoGebra and learning analytics. Such integration may further enhance spatial reasoning and provide richer data on learning processes.

Summary

Overall, the results and discussion demonstrate that Augmented Reality strategies offer a powerful approach to improving student spatial reasoning in mathematics classrooms. When integrated with sound pedagogy, AR enhances cognitive outcomes, engagement, and learning processes. These findings contribute to a more systematic understanding of AR's role in mathematics education and provide a foundation for future research and practice.

CONCLUSION

This study demonstrates that Augmented Reality offers a strong instructional strategy for improving students' spatial reasoning in mathematics classrooms. The findings show that

AR-based learning produces clear gains in overall spatial reasoning when compared to conventional instruction. Students who engaged with AR tools developed stronger abilities to visualize, rotate, and interpret three-dimensional mathematical objects. These skills are essential for understanding geometry and other spatially demanding mathematical topics.

The results confirm that spatial reasoning can be developed through intentional instructional design. AR supports this development by transforming abstract concepts into interactive visual experiences. Students do not only observe mathematical objects. They actively manipulate them. This active engagement strengthens conceptual understanding and supports deeper learning processes. AR also encourages inquiry, exploration, and collaboration, which further enhance learning outcomes.

Another important conclusion relates to student engagement. AR creates a learning environment that increases interest and participation. Students show higher motivation and sustained focus during AR-supported lessons. This engagement supports cognitive growth and reduces barriers often associated with mathematics learning. However, the study also shows that technology alone is not sufficient. Learning gains depend on how AR is integrated into pedagogy. Clear objectives, structured tasks, and teacher guidance remain critical.

The study highlights practical implications for mathematics education. AR is especially effective for topics involving three-dimensional structures and spatial transformation. Teachers should align AR activities with specific spatial reasoning goals. Professional development is also essential to ensure effective classroom implementation.

Overall, this research confirms that Augmented Reality is not merely a technological enhancement. It is a pedagogical tool that can meaningfully support spatial reasoning development when used purposefully. The findings contribute to mathematics education research and provide guidance for educators seeking to integrate AR into classroom practice in a systematic and effective way.

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