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Augmented Reality Game-Based Learning, Spatial Ability, and Learning Style: An Explanatory Mixed Methods

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ABSTRACT

This study investigates the effectiveness of Augmented Reality Game-Based Learning (AR-GBL) in enhancing seventh-grade students' spatial ability in geometry, using an explanatory mixed-methods design. The quantitative phase employed a quasi-experimental post-test-only control-group design involving 52 students from a public junior high school in Cirebon City, Indonesia. The experimental group received geometry instruction on flat-faced three-dimensional solids through AR-GBL, while the control group was taught conventionally. Data were collected using a spatial ability test and analysed through independent samples t-tests, mastery analysis, and simple linear regression. The results indicate a statistically significant difference in spatial ability between groups ($p < 0.05$), with AR-GBL contributing 32.9% of the variance in students' spatial performance and enabling both classical and individual mastery. The qualitative phase consisted of semi-structured student interviews and classroom observations to explain the quantitative results. Qualitative findings reveal that AR-GBL supported spatial understanding by strengthening three-dimensional visualization, facilitating mental rotation, increasing engagement, and enabling teacher-mediated reflection during learning activities. At the same time, initial technological adaptation and attentional regulation emerged as constraints that influenced individual learning trajectories. Integration of quantitative and qualitative findings shows that AR-GBL operates as a mediated learning environment rather than an autonomous instructional solution. These findings underscore the importance of pedagogical scaffolding to maximize the benefits of AR-based game-based learning for spatial ability development in geometry classrooms.

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1. INTRODUCTION

Spatial ability constitutes a fundamental cognitive skill in mathematics learning, particularly in geometry, where students are required to visualize, manipulate, and mentally transform three-dimensional objects. Research in mathematics education has long demonstrated that students' success in geometry is closely associated with their capacity for spatial visualization and mental rotation [1], [2], as an empirical academic correlation. However, many students still experience difficulties in geometry because their understanding often remains limited to surface-level visualization rather than deeper spatial reasoning [3], [4], due to conceptual visualization barriers. As a result, such limitations often lead to fragmented understanding and difficulties in solving geometry problems that involve complex spatial relationships.

Contemporary perspectives emphasize that spatial ability is not a fixed or innate attribute, but a cognitive capacity that can be developed through targeted instructional experiences, manifested in a malleable cognitive growth. Interaction with real or virtual objects provides learners with opportunities to construct and refine spatial understanding through active engagement [5], serving as a constructivist knowledge-building. In mathematics classrooms, however, instructional practices often rely on static two-dimensional representations, limiting students' opportunities to explore spatial transformations dynamically. As a result, there is a growing need for instructional approaches that bridge the gap between abstract geometric concepts and students' perceptual experiences through integrative conceptual synthesis.

In response to this challenge, technology-enhanced learning environments have gained increasing attention. Among these, Augmented Reality (AR) has emerged as a promising tool for supporting spatial cognition by overlaying virtual three-dimensional objects onto the real world, fixed by immersive perceptual enhancement. Prior studies suggest that AR-based learning environments can enhance students' engagement, support visualization, and promote higher-order thinking skills, including problem solving [6], [7]. By allowing learners to rotate, inspect, and manipulate objects in real time, AR offers representational affordances that are difficult to achieve through conventional instructional media, emphasizing mathematics education's position to present a rich and flexible reality for students' intellectual growth.

Although research on AR in mathematics education continues to grow, important gaps remain. Many previous studies focus mainly on general learning outcomes, while only a limited number specifically examine the effect of AR on students' spatial ability in junior high school geometry [8], [9]. In addition, most studies rely heavily on quantitative findings and provide limited explanation of how students experience and interact with AR during learning. As a result, the cognitive and classroom processes underlying AR effectiveness remain poorly understood. Existing research also shows that AR does not automatically improve learning, since students may experience distraction or cognitive overload when instructional guidance is insufficient [10], [11].

Moreover, individual differences among learners, such as learning style, have been discussed in the literature as factors that may shape how students engage with instructional environments. Learning styles have been categorized into visual, auditory, and kinaesthetic tendencies, suggesting that learners may respond differently to instructional media depending on their preferred learning modes [12], [13]. However, empirical evidence indicates that learning style should be interpreted cautiously, as it interacts with pedagogical design rather than determining learning outcomes in a deterministic manner [14]. In the context of AR-based learning, the role of learning style remains underexplored, particularly as an interpretive lens for understanding variation in students’ learning experiences.

Furthermore, prior research has highlighted the importance of instructional mediation in technology-enhanced learning. Student-centred and interactive environments require active teacher guidance to ensure that engagement with technology translates into conceptual understanding rather than superficial interaction [15], [16], [17]. Nevertheless, few studies have integrated quantitative evidence of AR effectiveness with qualitative analysis of classroom interaction to explain how AR supports spatial learning processes. This gap indicates the need for research that combines statistical evidence with a deeper exploration of students’ learning experiences.

To address these gaps, the present study investigates the effectiveness of Augmented Reality Game-Based Learning (AR-GBL) in enhancing seventh-grade students’ spatial ability in geometry, using an explanatory mixed-methods design. The quantitative phase examines whether AR-GBL leads to significantly higher spatial ability outcomes than conventional instruction, while the qualitative phase explores students’ experiences and classroom interactions to explain the quantitative results. To complete, learning style is incorporated as an interpretive construct to support the integration of findings, rather than as a statistically tested moderator that acts as a lens.

By combining quasi-experimental analysis with in-depth qualitative inquiry, this study seeks to provide a more comprehensive understanding of how and why AR-GBL influences the development of spatial ability. The integration of findings aims to illuminate the pedagogical mechanisms underlying statistical effects and clarify the conditions under which AR-based game-based learning is most effective in geometry classrooms.

Accordingly, this study is guided by the following research questions:

1) To what extent does Augmented Reality Game-Based Learning significantly improve students’ spatial ability compared with conventional instruction?
2) How do students describe the ways Augmented Reality Game-Based Learning supports or constrains their spatial understanding during gameplay and learning activities?
3) How do qualitative findings explain the quantitative results regarding the effects of Augmented Reality Game-Based Learning on students’ spatial ability across different learning styles?

Beyond addressing the stated research questions, this study offers several contributions to the field of mathematics education and educational technology research. Empirically, it extends existing work on augmented reality by providing evidence of its effectiveness in developing spatial ability within junior high school geometry, a context that remains underrepresented in prior studies. Methodologically, the study demonstrates the value of an explanatory mixed methods design for moving beyond outcome-based claims toward process-oriented explanations of learning with AR, thereby linking statistical effectiveness with classroom-level meaning-making. Conceptually, by positioning learning style as an interpretive construct rather than a deterministic variable, the study contributes a more nuanced perspective on individual differences in technology-enhanced learning. Collectively, these contributions inform both theory and practice by clarifying how AR-based game learning can be pedagogically orchestrated to support spatial reasoning in geometry classrooms.

2. METHOD

2.1 Research design

This study employed an explanatory sequential mixed-methods design [18] to investigate the effectiveness of Augmented Reality Game-Based Learning (AR-GBL) on students' spatial ability in geometry. The design consisted of two consecutive phases. The quantitative phase used a quasi-experimental approach to examine differences in spatial ability outcomes between instructional conditions, while the qualitative phase was conducted to explain and elaborate on the quantitative results through students' learning experiences and classroom interactions. This design enabled integrating statistical trends with experiential evidence, consistent with the explanatory logic of mixed-methods research.

2.2 Variables of the study

The independent variable was Augmented Reality Game-Based Learning (AR-GBL), a teaching approach that combined game-based activities with AR-supported three-dimensional visualization. The dependent variable was students' spatial ability, measured through geometry tasks involving spatial visualization, mental rotation, and spatial orientation.

Learning style was not treated as a statistical moderating variable. Instead, it functioned as an interpretive variable used to explain variations in students' learning experiences and responses to AR-GBL during the qualitative integration process. Learning styles were categorized into visual, auditory, and kinaesthetic tendencies based on students' questionnaire responses.

2.3 Research site and participants

The study took place during Grade 7 math class at a public junior high school in Cirebon City, Indonesia. The lesson focused mostly on geometry, specifically three-dimensional solids with flat faces. Participants were 52 seventh-grade students from two intact classes. One class (n = 28) was assigned to the experimental group, and the other (n = 24) to the control group. The class assignment followed a quasi-experimental design, using existing classroom groupings rather than random individual allocation. All students participated in the quantitative phase of the study.

For the qualitative phase, a purposive subsample of students from the experimental group was selected based on differences in their spatial ability performance and classroom engagement. These students took part in semi-structured interviews. Additionally, classroom observations were conducted during AR-GBL implementation to document instructional methodologies, student interactions, and patterns of engagement.

2.4 Instructional materials and learning context

The instructional intervention was integrated into the regular mathematics curriculum and focused on geometry topics related to flat-faced three-dimensional figures.

The intervention was implemented over four learning sessions, with each session lasting approximately 90 minutes.

In the experimental group, instruction was delivered through AR-GBL activities that enabled students to manipulate virtual geometric objects, rotate shapes, and explore spatial relationships through game-based tasks. The activities were designed to support spatial visualization, mental rotation, and spatial orientation processes.

The control group learned the same material through conventional instruction, including textbook explanations, board-based illustrations, and two-dimensional representations. To maintain comparability between groups, instructional duration, learning objectives, and content coverage were kept consistent.

2.5 Data collection procedures

Quantitative data were collected using a spatial ability test administered at the end of the instructional intervention. The test consisted of geometry-based tasks measuring spatial visualization, mental rotation, and spatial orientation. The instrument was adapted from established spatial ability indicators developed in previous studies in mathematics education [20], [21].

Content validity was evaluated through expert judgment involving two mathematics education lecturers and one junior high school mathematics teacher. Revisions were made based on feedback regarding item clarity, content relevance, and alignment with spatial ability indicators. Instrument reliability was tested using Cronbach's Alpha, resulting in a reliability coefficient of 0.82, which indicated good internal consistency.

Learning style data were collected through a structured questionnaire administered before the intervention. The questionnaire was used to support interpretive analysis of students' learning experiences rather than statistical moderation testing. Qualitative data were collected after the quantitative phase through semi-structured interviews and non-participant classroom observations. Interview questions explored students' experiences with AR-GBL, their perceived benefits and challenges, and the strategies they used to understand geometric concepts during gameplay. Observation focused on instructional flow, student participation, interaction with AR media, and problem-solving behaviour during learning activities.

2.6 Data analysis

Quantitative data were analyzed using inferential statistical techniques appropriate for quasi-experimental research [19]. Independent-samples comparisons were conducted to examine differences in spatial ability between the experimental and control groups. Descriptive statistics were also used to summarize general performance trends.

Because learning style functioned as an interpretive variable rather than a moderator, no statistical moderation analysis was conducted. Instead, learning style categories were used during the qualitative integration stage to interpret differences in students' experiences and engagement with AR-GBL.

Qualitative data from interviews and observation notes were analyzed thematically through familiarization, coding, theme development, and refinement. During the integration of mixed methods, qualitative themes were linked to quantitative findings through a narrative weaving strategy. This process helped explain how students' interactions with AR-GBL contributed to differences in spatial ability development across varied learning style tendencies.

3. RESULTS AND DISCUSSION

The quantitative analysis demonstrates that Augmented Reality Game-Based Learning (AR-GBL) produced a statistically significant improvement in students' spatial ability compared with conventional instruction.

3.1 Quantitative Findings (RQ1)

The post-test results show that students in the experimental group achieved a higher mean spatial ability score than those in the control group.

Table 1. Post-Test Mean Scores of Spatial Ability

Group	N	Mean	SD	95% CI
Experimental (AR-GBL)	28	87.14	6.82	[84.49, 89.79]
Control (Conventional)	24	74.63	7.11	[71.63, 77.63]

The mean score of 87.14 indicates that students exposed to AR-GBL reached a high level of spatial performance following the intervention. This average not only reflects strong overall achievement but also suggests that most students performed tasks involving visualization, mental rotation, and spatial transformation with a relatively high degree of accuracy. The distribution of scores further shows that performance was not concentrated among only a few high-achieving individuals, but was observed across a substantial proportion of the experimental group.

To determine whether the difference between the experimental and control groups was statistically significant, an independent-samples t-test was used. Before the analysis, we checked for normality and homogeneity of variance and found both to be true. The results showed a statistically significant difference in spatial ability scores between the two groups. This means that students who learned through AR-GBL did better than those who learned through traditional methods. This finding indicates that the improvement cannot be solely ascribed to random variation, but rather reflects a significant instructional impact associated with the AR-GBL intervention.

Table 2. Independent-Samples T-Test Results

Comparison	t	df	Sig. (2-tailed)	Mean Difference	Cohen's d	95% CI of Difference
Experimental vs Control	6.42	50	0.000	12.51	1.79	[8.60, 16.42]

The significance value ($p < 0.05$) confirms that the observed difference was unlikely to occur by chance. The experimental group outperformed the control group by a mean difference of 12.51 points. In addition, the effect size analysis produced a Cohen's d value of 1.79, indicating a large practical effect of AR-GBL on students' spatial ability. The confidence interval further shows that the true mean difference consistently favoured the experimental group.

In addition to statistical significance, mastery analysis provided further pedagogical evidence of the intervention's effectiveness. Students in the experimental group achieved both individual mastery standards and classical mastery standards, indicating that learning gains were distributed across the class rather than concentrated among a small number of high-achieving students.

Table 3. Mastery Test Results

Mastery Type	**z-value**	**z-table**	**Interpretation**
Classical mastery	4.24	1.64	Achieved
Individual mastery	2.18	1.64	Achieved

Both classical and individual mastery results exceed the critical value ($z = 1.64$), indicating that the proportion of students reaching the minimum competency standard was statistically significant. These findings suggest that AR-GBL not only elevated overall mean performance but also ensured that learning gains were distributed across the class, fulfilling both aggregate and individual mastery criteria in a meaningful way.

To further ascertain the degree of instructional contribution, a simple linear regression analysis was performed to evaluate whether participation in AR-GBL significantly predicted students' spatial ability outcomes. This analysis estimates the extent to which the intervention accounts for variance in spatial ability scores, elucidating the efficacy of AR-GBL as a contributor in students' spatial development.

Table 4. Simple Linear Regression Results

Indicator	**Value**
Significance (Sig.)	0.001
Coefficient of Determination (R^2)	0.329 (32.9%)
Regression Coefficient (β)	0.574
95% CI for β	[0.31, 0.84]

The regression analysis indicates that AR-GBL explained 32.9% of the variance in students' spatial ability scores. This result demonstrates a meaningful instructional contribution of AR-GBL to spatial ability development, while factors beyond the scope of this study may account for the remaining variance.

This figure illustrates an interaction pattern between the instructional model and learning style in relation to students' spatial ability. The plot visualizes how Augmented Reality Game-Based Learning (AR-GBL) consistently yields higher spatial ability outcomes than conventional instruction across visual, auditory, and kinesthetic learning styles. The figure is intended to support mixed-methods interpretation and does not represent inferential statistical testing.

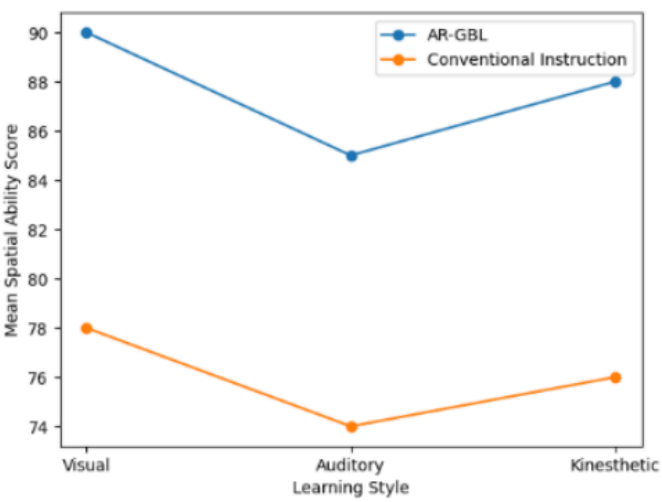

Figure 1. Interaction Plot

The interaction plot suggests a stable advantage of AR-GBL over conventional instruction across all learning style categories. Visual learners appear to benefit most, consistent with the AR affordance of three-dimensional visualization and object manipulation. Kinesthetic learners also show relatively high spatial performance under AR-GBL, plausibly due to interactive and exploratory gameplay mechanics. Auditory learners demonstrate comparatively lower gains, although AR-GBL still outperforms conventional instruction, indicating that visual–spatial affordances may partially compensate for modality preferences.

Importantly, the roughly parallel lines indicate that learning style does not reverse the direction of the instructional effect, but rather shapes the magnitude of spatial gains. This pattern aligns with the qualitative findings showing that AR-GBL supports spatial understanding through external visualization, mental rotation, and sustained engagement, while individual differences influence how effectively students appropriate these affordances.

Overall, the quantitative results show that Augmented Reality Game-Based Learning greatly improves Grade 7 students' spatial skills in geometry. The experimental group exhibited superior post-test performance, with statistically significant differences relative to the control group, successful mastery at both classical and individual levels, and a considerable instructional impact as evidenced by regression analysis. These results provide a robust empirical basis for the ensuing qualitative phase, which seeks to elucidate the mechanisms and rationale underlying AR-GBL's facilitation of spatial learning.

3.2 Qualitative Findings (RQ2)

Qualitative analysis of interview transcripts and classroom observations reveals that Augmented Reality Game-Based Learning (AR-GBL) reshaped students' spatial understanding through direct interaction with three-dimensional representations, altered cognitive strategies during problem-solving, and altered engagement patterns. At the same time, the data reveal constraints on technological adaptation and attentional regulation during gameplay.

1) Support for spatial visualization and object recognition

Students consistently described AR as enabling clearer perception of geometric objects compared with static textbook images. Interview data indicate that the ability to view objects from multiple angles reduced ambiguity in identifying faces, edges, and vertices.

> *"When using AR, I can see the shape from the side and the back so that I can imagine the real form more clearly"*(INT-S1).

Observational data strongly support this account. Students were observed repeatedly rotating virtual solids before answering geometry questions during AR-based sessions. Instead of answering right away, many students moved the objects around to see how they were related in space.

Students repeatedly rotated virtual objects on their devices before selecting answers, often pausing to observe orientation changes (OBS-1). This pattern suggests that AR functioned as an externalized spatial scaffold, allowing students to offload part of the visualization process onto the digital environment. Instead of relying solely on internal imagery, students used AR to stabilize and verify spatial representations, which aligns with the improved post-test performance observed in the quantitative phase.

2) Facilitation of mental rotation and anticipatory reasoning

Beyond visualization, students reported changes in how they approached spatial problems. Several interview excerpts indicate that students began to adopt deliberate mental rotation strategies supported by AR interaction.

> *"I usually rotate the shape first before answering, so I'm more confident"* (INT-S3).

This statement reflects a shift from guessing or memorizing to strategic spatial reasoning. Observation data corroborate this shift. Students were frequently seen predicting how objects would appear after rotation and then confirming their predictions by manipulating the AR model.

Students verbally predicted how an object would look after rotation, then checked their predictions using the AR model (OBS-2). This interaction between prediction and confirmation suggests that AR-GBL supported the coordination of internal mental rotation with external visual feedback. Such coordination likely contributed to the statistically significant gains in spatial ability, particularly for tasks requiring transformation and orientation.

3) Engagement, persistence, and time-on-task

Students repeatedly emphasized that AR-GBL made geometry learning more engaging. Interview data indicate that game-based elements sustained attention and reduced boredom.

> *"Learning feels less boring because it's like playing a game while still thinking"* (INT-S2).

Observational evidence supports this claim. Compared with conventional lessons, AR-based sessions showed longer on-task periods, fewer off-task conversations, and higher levels of peer interaction focused on task completion. Students remained engaged for longer periods during AR-based activities than during textbook-based instruction, with frequent task-related peer discussion (OBS-1). From an analytical perspective, this increased engagement appears to function as an enabling condition rather than a direct cognitive mechanism. By sustaining attention and motivation, AR-GBL created opportunities for repeated interaction with spatial representations, an essential factor in developing spatial competence.

4) Constraints related to cognitive load and technological adaptation

Despite these benefits, qualitative data also reveal notable constraints. Several students reported initial difficulty using the AR application.

"At first, I was confused about how to use it, but after a few times I got used to it" (INT-S2).

Classroom observations confirm that technical challenges were most prominent during early sessions.

A small number of students required assistance in operating the AR application during the first lesson. (OBS-2). Additionally, some students acknowledged that game mechanics occasionally diverted attention from conceptual goals.

"Sometimes I focus more on playing than on the question" (INT-S3).

This concern was also observed in practice, particularly when students competed for speed rather than accuracy. In several instances, students prioritized game progression over explaining their reasoning (OBS-1). These findings suggest that AR-GBL initially increases cognitive load, as students must simultaneously manage interface navigation, game rules, and mathematical reasoning. Without instructional mediation, this load risks overshadowing conceptual learning.

5) Role of teacher mediation in regulating learning focus

Observation data highlight teacher intervention as a critical factor in mitigating these constraints. Teachers frequently redirected students' attention from gameplay to geometric reasoning. The teacher prompted students to explain why a rotated object still represented the same solid, linking gameplay actions to formal concepts (OBS-2). Such mediation appeared to recalibrate students' focus, transforming game actions into reflective learning moments. This indicates that AR-GBL is most effective not as a standalone technological solution, but as part of a guided instructional ecology.

In short, the qualitative findings suggest that AR-GBL supports spatial understanding by externalizing visualization, facilitating coordinated mental rotation, and sustaining engagement through game-based interaction. These affordances provide a plausible explanation for the significant quantitative gains in spatial ability observed in the experimental group.

However, the data also caution against uncritical adoption. AR-GBL introduces new forms of cognitive and attentional demand that require careful instructional regulation. The effectiveness of AR-GBL, therefore, depends not only on the technology itself but on how teachers orchestrate interaction, scaffold reflection, and align gameplay with conceptual goals. In this sense, AR-GBL functions less as an autonomous instructional tool and more as a mediational resource whose pedagogical value emerges through guided use. This interpretation directly informs the integration phase (RQ3), in which qualitative evidence explains why AR-GBL produced strong yet non-exhaustive effects on students' spatial ability.

3.3 Integration Findings (RQ3)

The explanatory mixed methods design adopted in this study requires that quantitative results be interpreted in light of qualitative evidence to clarify how and why the observed effects occurred. While the quantitative phase demonstrated that Augmented Reality Game-Based Learning (AR-GBL) significantly improved students' spatial ability, numerical indicators alone could not account for the learning processes underlying these outcomes. The qualitative phase, therefore, functioned as an explanatory lens, providing insight into students' cognitive strategies, engagement patterns, and interaction with AR-supported learning environments.

To achieve analytic integration, this study employs a joint display that aligns key quantitative results with corresponding qualitative evidence. This approach makes explicit the connections between statistical outcomes and lived classroom experiences, thereby systematically articulating the explanatory function of the qualitative findings.

Table 5. Joint Display of Quantitative Results and Qualitative Explanations

Quantitative Findings (RQ1)	**Qualitative Evidence (RQ2)**	**Integrated Interpretation (RQ3)**
AR-GBL produced a significantly higher spatial ability mean score than conventional instruction (M = 87.14; Sig. = 0.000)	"When using AR, I can see the shape from the side and the back." (INT-S1)	Higher mean performance is attributable to multi-perspective visualization that stabilized students' internal spatial representations
Students rotated objects repeatedly before answering (OBS-1)	Quantitative gains are explained by AR-supported external visualization, which reduced ambiguity and supported stable spatial representations	Repeated rotation indicates strategic verification behavior, suggesting that AR externalizes mental rotation processes and strengthens spatial reasoning accuracy.
AR-GBL accounted for 32.9% of the variance in spatial ability outcomes ($R^2 = 0.329$)	"At first, I was confused, but after a few times I got used to it." (INT-S6)	The moderate R^2 reflects adaptation effects; initial cognitive load reduced as familiarity increased, allowing AR affordances to translate into measurable gains.
Some students focused on gameplay rather than concepts (OBS-6)	Partial variance explained reflects differences in how students appropriated AR affordances and regulated attention during gameplay	Partial variance explained reflects differential regulation of attention; conceptual gains depended on how students appropriated game features.
Experimental group achieved both classical (z = 4.24) and individual mastery (z = 2.18)	"Learning feels less boring because it's like playing a game." (INT-S5)	Mastery was supported by increased motivation and sustained engagement, which expanded effective learning time.

Students showed longer on-task behavior (OBS-5)	Mastery attainment is linked to sustained engagement and increased time-on-task during AR-GBL activities.	Extended time-on-task functioned as a mediating mechanism linking engagement to achievement gains.
Consistent performance advantage of AR-GBL across students	Visual inspection of AR objects, manipulation, and peer discussion were dominant learning behaviors (OBS-2, OBS-5)	Learning style is interpreted as an analytic lens: visual and kinesthetic tendencies appear more readily supported by AR affordances, while auditory-oriented learners benefit when gameplay is accompanied by teacher scaffolding
Learning gains were not uniform.	Teacher prompted conceptual explanation during gameplay (OBS-4)	Teacher mediation functioned as a regulatory mechanism that aligned engagement with conceptual understanding

In this study, learning style is positioned as an interpretive construct derived from qualitative patterns and illustrative visualization rather than as a statistically tested moderating variable. The joint display indicates that the effectiveness of Augmented Reality Game-Based Learning (AR-GBL) in enhancing spatial ability cannot be explained solely by technological affordances or game mechanics. Instead, the observed quantitative gains are best understood as emerging from a convergence of qualitative processes, including strengthened three-dimensional visualization, the adoption of deliberate spatial reasoning strategies, sustained learner engagement, and ongoing instructional mediation.

Qualitative evidence further clarifies why AR-GBL accounted for a substantial yet incomplete proportion of variance in spatial outcomes, underscoring the influence of individual adaptation and pedagogical regulation in shaping learning trajectories. Through this integrative analysis, RQ3 demonstrates that AR-GBL functions as a mediated learning environment rather than an autonomous instructional solution. The joint display, therefore, fulfills the explanatory intent of the mixed methods design by systematically linking statistical effectiveness to classroom-level meaning-making processes.

3.4 Discussion

The findings of this explanatory mixed-methods study affirm that Augmented Reality Game-Based Learning (AR-GBL) constitutes a pedagogically effective approach for enhancing students' spatial ability in geometry. Quantitative evidence (RQ1) indicates that students exposed to AR-GBL significantly outperformed peers in conventional instruction. This result supports the broader view that spatial ability is a malleable cognitive capacity that develops through interaction with representational environments rather than a fixed individual trait [5], [20]. Within geometry learning, where abstract spatial relationships often challenge learners, AR-GBL appears to offer representational conditions that are more aligned with students' cognitive needs than static two-dimensional media [21], [22]. Recent studies in AR-supported mathematics learning have similarly reported that immersive, interactive visualization environments can improve students' conceptual understanding, engagement, and spatial reasoning.

From a cognitive and instructional perspective, the qualitative findings (RQ2) help explain why these gains emerged. Students' descriptions and classroom observations show that AR-GBL supported clearer visualization of geometric objects through three-dimensional representation and manipulation. Prior research has consistently shown that students' difficulties in geometry are closely tied to limitations at the visualization stage of geometric thinking [3], [15]. By enabling learners to rotate, inspect, and reorient objects dynamically, AR-GBL appears to strengthen foundational spatial visualization processes that are often underdeveloped in conventional instruction. Similar conclusions have been reported in recent AR-education studies, which emphasize that interactive visualization can strengthen students' spatial perception and reduce abstraction in STEM learning environments.

In addition to visualization, AR-GBL facilitated mental rotation and strategic spatial reasoning. Furthermore, students' deliberate rotation of objects before answering tasks reflects a shift toward more reflective, verification-oriented problem-solving behavior. Mental rotation has been conceptualized as a core component of spatial ability involving the transformation of internal object representations [1]. In this study, AR-GBL externalized this cognitive process, allowing students to coordinate internal reasoning with immediate visual feedback. Such coordination likely reduced uncertainty and supported more accurate spatial judgments, which is consistent with prior findings that AR environments can enhance higher-order cognitive skills when learners actively engage with virtual objects [6], [7].

The mixed methods integration (RQ3) provides a more nuanced understanding of the magnitude and limits of AR-GBL's effectiveness. While quantitative analysis indicates that AR-GBL accounted for a substantial proportion of variance in spatial ability outcomes, qualitative evidence clarifies why this influence was not exhaustive. Students differed in their initial adaptation to AR interfaces and in their ability to regulate attention during gameplay. These findings echo concerns raised in earlier studies that technology-enhanced learning environments may increase cognitive load [23], [24], particularly during early stages of use, if learners must simultaneously manage interface navigation and conceptual processing [10], [11]. Consequently, AR-GBL's effectiveness should be understood as conditional rather than automatic.

A key explanatory factor emerging from the qualitative data is teacher mediation. Observational evidence shows that teachers actively redirected students' attention from game mechanics to conceptual reflection, prompting explanations of spatial transformations and reinforcing mathematical meaning. This finding aligns with pedagogical arguments that student-centered, technology-supported learning environments remain dependent on instructional guidance to foster deep understanding [15]. Without such mediation, engagement risks remaining at the level of surface interaction rather than being transformed into conceptual learning.

Learning style, although not treated as a statistically tested moderator, also contributed interpretively to the explanation of differential learning experiences. Classification of learning tendencies into visual, auditory, and kinesthetic modalities suggests that learners may engage differently with representational media [12], [13]. However, individual learning characteristics should not be interpreted deterministically, as they interact with pedagogical design rather than rigidly determining learning outcomes [14].

In this study, pedagogical scaffolding appeared to mitigate potential mismatches between learning preferences and instructional affordances.

This finding carries important practical implications for classroom teaching. First, AR-GBL should be integrated into lessons as part of structured pedagogical activities rather than used as an isolated technological tool. Teachers need to provide clear conceptual prompts, guide reflective discussion, and monitor students' attention during gameplay. Second, successful implementation requires gradual orientation to AR interfaces so that students can focus on spatial reasoning rather than technological adjustment. Third, collaborative discussion during AR activities appears important because it encourages students to verbalize and refine their spatial thinking processes. These implications suggest that the effectiveness of AR-based learning depends not only on technological affordances but also on the quality of instructional design and teacher facilitation.

Overall, the synthesis of findings across RQ1–RQ3 demonstrates that AR-GBL enhances spatial ability not merely by introducing advanced technology, but by reorganizing students' spatial meaning-making processes within a guided instructional context. The quantitative gains observed are best understood as emergent outcomes of multiple interacting factors, including representational support, strategic reasoning, sustained engagement, and pedagogical regulation. This integrated interpretation reinforces the value of explanatory mixed-methods designs in educational technology research, as they enable statistical effectiveness to be meaningfully linked to classroom-level learning processes.

4. CONCLUSION

This explanatory mixed-methods study demonstrates that Augmented Reality Game-Based Learning (AR-GBL) is effective in improving seventh-grade students' spatial ability in geometry. Quantitative findings show that students taught through AR-GBL achieved significantly higher spatial ability scores and mastery outcomes than those who received conventional instruction.

The findings also show that spatial visualization plays a central role in supporting students' geometry learning. Qualitative evidence indicates that AR-GBL helped students visualize, rotate, and manipulate three-dimensional objects more effectively, thereby strengthening spatial reasoning and supporting a deeper understanding of geometric relationships. Another important conclusion concerns the role of teacher scaffolding. The effectiveness of AR-GBL did not emerge from technology alone, but from guided instructional support during learning activities. Teacher mediation helped students connect gameplay experiences with mathematical concepts, regulate attention, and engage in reflective spatial reasoning.

Based on these findings, AR-GBL should be implemented as a pedagogically guided instructional approach rather than as a standalone technological tool. Teachers need to provide explicit conceptual guidance and structured reflection during AR-based activities. Future research may examine AR-supported spatial learning over longer instructional periods and explore additional learner characteristics related to spatial reasoning development.

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