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Effect Of Augmented Reality-Based Textbook On Geometry Spatial Ability Of Deaf Students: A-B-A SSR

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***Abstract*:**
Mathematical spatial ability plays a crucial role in geometry learning, particularly in visualizing and manipulating three-dimensional objects. However, students with hearing impairment often face difficulties in developing spatial reasoning due to limited access to dynamic and interactive visual learning media, which can hinder their overall performance in geometry and related subjects. Although Augmented Reality (AR) has been widely implemented in mathematics education, empirical evidence on its effectiveness in improving spatial ability among deaf students, particularly using a Single Subject Research (SSR) design, remains limited. This study aims to examine the effect of an AR-based mathematics textbook on the mathematical spatial ability of three deaf students at a special senior high school (SMALB). A mixed-methods embedded design was employed, with quantitative data collected using a Single Subject Research (A1–B–A2) model and qualitative data obtained from observations, interviews, and questionnaires to explore students' learning experiences. Quantitative data were analyzed using visual and quantitative techniques in a single-subject research design. The findings indicate consistent improvement during the intervention phase, supported by positive trend direction, clear level changes, immediacy of effect, and 0% data overlap between baseline and intervention across subjects. These results provide evidence of the effectiveness of AR-based mathematics textbooks in improving and sustaining mathematical spatial ability within the observed cases of deaf students in geometry learning.

Keywords: Augmented Reality; mathematical spatial ability; deaf students; geometry learning; Single Subject Research.

Introduction

Mathematical spatial ability is widely acknowledged as a foundational cognitive component underpinning geometry learning, particularly in topics involving three-dimensional objects such as cubes, rectangular prisms, and other spatial structures. Spatial reasoning is not a unitary construct but rather a constellation of interrelated processes that include spatial visualization, mental rotation, spatial orientation, and spatial representation. These processes enable learners to construct internal images of objects, manipulate them mentally, shift perspectives, and interpret spatial relationships across multiple viewpoints (Linn & Petersen, 1985; Lu et al., 2026). Within geometry education, such abilities are indispensable because students are frequently required to move flexibly between symbolic expressions, two-dimensional diagrams, and imagined three-dimensional configurations. The capacity to mentally manipulate and reorganize spatial information serves as a vital link between visual perception and abstract mathematical reasoning.

Recent empirical evidence further substantiates the structural connection between spatial reasoning and mathematics achievement. A large-scale meta-analysis conducted by Lu et al. (2026) reported a moderate yet consistent correlation ($r = 0.31$) between spatial reasoning and overall mathematics performance across 62 empirical studies. Notably, stronger associations were identified in geometry and logical reasoning domains compared to arithmetic tasks, indicating that spatial cognition is particularly integral to mathematical areas requiring abstraction and transformation of visual-spatial information. Complementary studies examining spatial–numerical mapping and mental transformation processes similarly demonstrate that spatial competencies significantly predict geometry performance and higher-order mathematical reasoning (Otálora & Taborda-Osorio, 2025; Tang & Wong, 2026). These findings reinforce theoretical arguments that spatial reasoning is not merely supportive but structurally intertwined with the construction of mathematical representations and problem-solving strategies.

Despite its recognized importance, a considerable body of research indicates that many students encounter substantial difficulties when required to visualize and manipulate three-dimensional forms. Challenges frequently arise in interpreting nets of solids, determining hidden faces, calculating surface area and volume, and performing mental rotations of composite structures (Buliali et al., 2021; Isharyadi & Herman, 2022). Limited spatial reasoning skills often result in misconceptions, procedural reliance without conceptual grounding, and fragmented knowledge structures. Systematic reviews in geometry education emphasize that dynamic visualization and spatial thinking remain critical yet underdeveloped dimensions of classroom instruction (Weigand et al., 2025). Traditional pedagogical approaches, which often rely heavily on static textbook diagrams and verbal explanation, may insufficiently support the cognitive demands of dynamic spatial transformation. Without adequate visual scaffolding, learners are required to mentally simulate complex transformations, increasing cognitive load and limiting conceptual consolidation.

In response to these challenges, the integration of digital technologies in mathematics education has expanded significantly. Among emerging technologies, augmented reality (AR) has attracted considerable scholarly attention due to its capacity to merge virtual three-dimensional objects with real-world environments in real time (Azuma, 1997). Recent meta-analytic evidence indicates that AR significantly improves learning outcomes and student motivation in educational contexts (Garzón et al., 2020). Unlike conventional two-dimensional visualizations, AR enables learners to interact directly with manipulable 3D representations, rotate objects, observe hidden surfaces, and explore spatial structures from multiple perspectives. Such affordances closely align with the cognitive processes underlying spatial reasoning. These capabilities are particularly relevant in geometry learning and hold strong potential for supporting deaf students, who rely predominantly on visual processing. Empirical investigations demonstrate that AR-based instructional environments enhance spatial visualization, mental rotation, and learner engagement by externalizing otherwise abstract spatial transformations (Kaufmann & Schmalstieg, 2003; Weigand et al., 2025). Experimental and quasi-experimental studies further report that AR integration in mathematics instruction improves conceptual understanding, spatial ability, and motivation across primary and secondary educational levels (Elmalı & Çıtak, 2026; Koparan et al., 2023; Zapata et al., 2024). High-impact international research also confirms that immersive and interactive 3D environments significantly strengthen spatial perception and spatial relations through embodied exploration (Kaźmierczak et al., 2025; Zou et al., 2025).

These findings suggest that AR is not merely a technological enhancement but an evidence-based pedagogical tool capable of addressing cognitive barriers inherent in spatial geometry learning (Kaźmierczak et al., 2025; Yang et al., 2026). By providing dynamic and manipulable representations, AR reduces the cognitive burden associated with purely mental reconstruction of spatial structures and facilitates gradual internalization of spatial schemas (Koparan et al., 2023). In contrast to static diagrams, AR environments allow learners to externalize transformation processes before consolidating them internally, thereby supporting deeper conceptual processing. This is especially beneficial for deaf learners, whose visual-oriented cognitive processing requires dynamic and manipulable representations to support conceptual understanding.

Nevertheless, while the effectiveness of AR in general student populations has been increasingly documented, empirical evidence regarding its implementation for students with hearing impairment remains limited. Deaf and hard-of-hearing (DHH) learners possess distinctive learning characteristics, particularly in their reliance on visual channels for information processing. Visual-spatial representation plays a central role in their cognitive development and problem-solving processes (Blatto-Vallee et al., 2007). At the same time, research indicates that DHH students frequently encounter barriers in accessing complex mathematical content due to linguistic constraints, limited incidental learning opportunities, and restricted access to auditory explanations (Alqahtani, 2025). These barriers may be especially pronounced in abstract domains such as geometry, where conceptual understanding often depends on precise mathematical language and dynamic explanation.

The visual strengths of deaf learners present both opportunities and challenges (Blatto-Vallee et al., 2007; Thom & Weber, 2026). On one hand, enhanced visual attention and spatial awareness may provide cognitive advantages in tasks involving visual manipulation. On the other hand, insufficiently adapted instructional media may hinder abstraction and generalization, particularly when instructional design does not align with students' communication needs (Alqahtani, 2025). In many educational contexts, including Indonesia, inclusive education policies formally guarantee equal access for students with disabilities through special schools (SLB) and inclusive settings. However, practical challenges persist in designing instructional materials that align with the communication needs and cognitive profiles of deaf students. Instructional media must therefore be not only visually rich but also interactive, manipulable, and conceptually coherent.

Previous research in special education underscores the importance of concrete and visually interactive learning tools for supporting conceptual understanding among deaf learners (Anwar et al., 2024; Su et al., 2025). Technology-enhanced environments that promote meaningful interaction can influence not only performance outcomes but also students' engagement and learning experiences (Bond et al., 2020; Nisa, 2019). However, most prior studies rely on group-based designs, which may not adequately capture individual learning variability in special education contexts.

Despite the growing body of research on AR in mathematics education, previous studies have primarily focused on general student populations and have largely employed group-based experimental or quasi-experimental designs. These approaches, while valuable, tend to overlook individual learning trajectories and may not adequately capture the variability characteristic of special education contexts. Furthermore, empirical evidence specifically addressing the effectiveness of AR-based instructional materials for deaf students, particularly in developing mathematical spatial ability, remains limited.

In contrast to prior studies, the present research positions itself at the intersection of three underexplored dimensions: (1) the use of AR-based mathematics textbooks as instructional media, (2) a focus on deaf learners with distinct visual-cognitive characteristics, and (3) the application of a Single Subject Research (A1–B–A2) design to capture detailed individual learning changes. By integrating these elements within a mixed methods framework, this study offers a more nuanced understanding of how AR-based instruction influences spatial ability development in inclusive and special education settings.

Based on these considerations, this study aims to analyze the effectiveness of an augmented reality-based mathematics textbook in improving the mathematical spatial ability of deaf students in geometry learning. The integration of dynamic AR visualization, individualized SSR methodology, and the specific cognitive characteristics of deaf learners constitutes the central novelty of this research and offers both theoretical and practical implications for inclusive geometry education.

Research Methods

This study employed a mixed-methods approach using an embedded design in which quantitative data served as the primary source of analysis and qualitative data were incorporated to enrich interpretation (Creswell & Creswell, 2018). The quantitative component was implemented through a Single Subject Research (SSR) framework using an A1–B–A2 design. This design enables systematic examination of individual performance changes across baseline, intervention, and withdrawal phases and is widely applied in special education due to its suitability for small samples and its capacity to capture intra-individual variability (Prahmana, 2021). Recent methodological discussions emphasize the importance of careful visual analysis and transparent reporting in strengthening the rigor of single-case research (Aldawoud, 2025).

The study was conducted at SLBN Ungaran, Semarang Regency, Central Java, Indonesia. Although the class consisted of ten Grade XI deaf students, purposive sampling was used to select three participants who demonstrated persistent difficulties in spatial geometry learning and were able to participate consistently throughout all phases. SSR prioritizes detailed individual analysis rather than statistical generalization; therefore, focusing on three subjects aligns with established single-case principles. Ethical approval was obtained from the school and relevant authorities, and informed consent was secured from students' guardians. The study adhered to ethical standards for research involving human participants, including confidentiality, voluntary participation, and the right to withdraw at any time. Communication accessibility during data collection was ensured through written explanations, visual supports, and sign language facilitation. Participants were anonymized as Subject 1, Subject 2, and Subject 3.

The A1–B–A2 design consisted of nine sessions, with three sessions in each phase. Each session lasted approximately 90 minutes. During the initial baseline phase (A1), students' mathematical spatial abilities were measured without the use of the augmented reality (AR)-based textbook to establish stable baseline performance. Baseline stability is essential in SSR because it supports attribution of subsequent changes to the intervention rather than to extraneous factors (Prahmana, 2021). Conventional textbook-based instruction was used during this phase.

The intervention phase (B) involved implementation of an AR-based mathematics textbook developed using the Assemblr platform. A marker-based configuration integrated with printed textbook materials was employed. Instruction focused on cube and rectangular prism topics, including elements of solids, nets, surface area, volume, and spatial representation of stacked cubes. Students interacted with three-dimensional virtual models through mobile devices, allowing them to rotate objects, manipulate orientations, and observe dynamic net-to-solid transformations. Instruction was organized in small groups to ensure active engagement and equitable access to devices. The AR environment was designed to externalize spatial transformations that are typically processed mentally, thereby supporting spatial reasoning development.

The withdrawal phase (A2) examined maintenance effects after AR removal. Equivalent spatial ability assessments were administered to determine whether improvements persisted beyond the intervention phase, thereby strengthening internal validity within SSR logic. The dependent variable was mathematical spatial ability, operationalized into four indicators: spatial orientation, spatial visualization, spatial transformation, and spatial representation. These were assessed through five geometry-based items administered at the end of each session, resulting in nine repeated measurements per participant. Scores ranged from 0 to 100. Equivalent test forms were constructed to maintain consistent cognitive demand while minimizing practice effects. Content validity of the AR textbook and spatial instrument was established through expert validation involving a university supervisor and a mathematics teacher for deaf students.

Quantitative data were analyzed descriptively following SSR procedures. Within-condition analysis examined level, trend, stability, and variability. Between-condition analysis evaluated level change, immediacy of effect, and percentage of data overlap across phases. Non-overlap was further quantified using the Non-overlap of All Pairs (NAP) index to support effect estimation across phases. Visual inspection of graphed data served as the primary analytic approach (Aldawoud, 2025). Data stability was determined when at least 80% of data points fell within a defined stability envelope. Level was defined as the mean score within each phase, while trend direction was identified based on the slope of data points across sessions. Interpretation also considered non-overlap and effect estimation principles recommended in SCRD literature (Chen & Wang, 2022; Travers et al., 2026), and all data points were transparently reported in line with methodological recommendations (Travers et al., 2026).

Qualitative data were collected through structured observations, semi-structured interviews, and a 12-item Likert-scale questionnaire assessing students' perceptions of clarity, engagement, and usefulness of AR-supported instruction. Observation and interview data were analyzed using thematic analysis involving data familiarization, initial coding, categorization, and theme development. To enhance trustworthiness, data triangulation was applied across multiple sources. The Likert-scale questionnaire was analyzed descriptively to support interpretation of qualitative findings. Integration of qualitative and quantitative data was conducted at the interpretation stage, where qualitative insights were used to explain and contextualize trends observed in the SSR data within the embedded mixed methods framework (Creswell & Creswell, 2018).

Results and Discussions

The SSR findings demonstrate a clear functional relationship between the implementation of the AR-based textbook and improvements in students' spatial ability. The consistent shift in level, direction, and data separation across all subjects at the onset of the intervention phase indicates that the observed improvements were systematically associated with the introduction of AR-supported instruction rather than occurring randomly. The replication of this pattern across three participants strengthens internal validity and confirms the effectiveness of the intervention within single-case research logic (Aldawoud, 2025; Prahmana, 2021).

During the initial baseline phase (A1), spatial ability scores for all three subjects remained relatively stable at low to moderate levels. This limited performance can be attributed to the abstract nature of spatial geometry concepts, which typically require mental manipulation of three-dimensional objects. For deaf students, who depend significantly on visual processing, the lack of dynamic and manipulable representations may impede the cultivation of precise spatial comprehension. As a result, students tended to rely on guessing strategies or incomplete mental representations, indicating a need for more visually explicit instructional support.

As presented in Table 1, all subjects demonstrated substantial positive level changes between baseline (A1) and intervention (B), accompanied by 0% overlap between data points across these phases. The Non-overlap of All Pairs (NAP) analysis, in addition to visual analysis, produced a value of 1.00 for all subjects, signifying a robust intervention effect with total separation between baseline and intervention data. This finding confirms that all intervention data points consistently exceeded baseline performance.

Table 1. Mean Spatial Ability Scores and SSR Indicators Across Phases (A1-B-A2)

Subject	Mean A1	Mean B	Mean A2	Level Change (A1-B)	Overlap A1-B (%)	Maintenance (A2 vs A1)
S1	61	92	89,3	+29	0%	Improved
S2	48,7	85,3	86,7	+42	0%	Improved
S3	69	88	82,7	+13	0%	Improved

Subject 1 improved from a mean score of 61 during A1 to 92 during B (+29 points). Subject 2 demonstrated the most substantial increase, rising from 48.7 to 85.3 (+42 points), while Subject 3 improved from 69 to 88 (+13 points). The greater improvement observed in Subject 2 may be associated with lower initial spatial ability, as students with limited prior competence tend to benefit more from concrete and interactive visual representations. In contrast, Subject 3, who started with relatively higher baseline performance, showed a smaller gain, which may indicate a ceiling effect where improvement opportunities become more limited. These differences highlight how AR-based instruction can provide differentiated benefits depending on students' initial ability levels.

Importantly, mean scores in the withdrawal phase (A2) remained substantially higher than baseline levels for all subjects, indicating maintenance of learning gains beyond direct intervention exposure. The presence of immediate level change at phase transition, positive trend direction, and zero overlap collectively strengthen the argument for a functional relationship between AR-based instruction and spatial ability enhancement.

The session-by-session data further clarify the dynamics of change. As shown in Figure 1, for Subject 1, baseline scores were stable but limited. Immediately following the introduction of the AR-based textbook, a sharp increase in performance was observed. This immediate effect, occurring precisely at the onset of phase B, strengthens causal inference within SSR logic. The upward trend across intervention sessions suggests progressive acquisition rather than novelty-driven fluctuation. Although a slight decrease occurred during A2 relative to peak intervention performance, the scores remained clearly separated from baseline levels, indicating retention of learning outcomes.

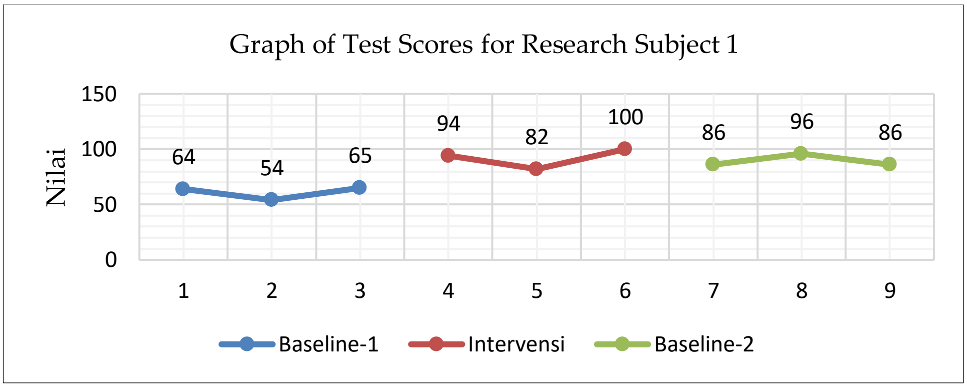

Figure 1. Spatial Ability Scores Across Sessions for Subject 1

As shown in Figure 2, Subject 2 displayed the lowest baseline scores among participants, indicating substantial initial difficulty in spatial geometry. However, the intervention produced an immediate and pronounced level change. The sharp shift at the onset of phase B reflects high responsiveness to dynamic visual scaffolding. Students with lower initial spatial competence often benefit more significantly from interactive three-dimensional visualization because such tools externalize transformation processes that would otherwise remain cognitively demanding (Koparan et al., 2023; Weigand et al., 2025). During the withdrawal phase, Subject 2 maintained performance above the baseline and even slightly above the intervention mean, suggesting the consolidation of spatial reasoning strategies.

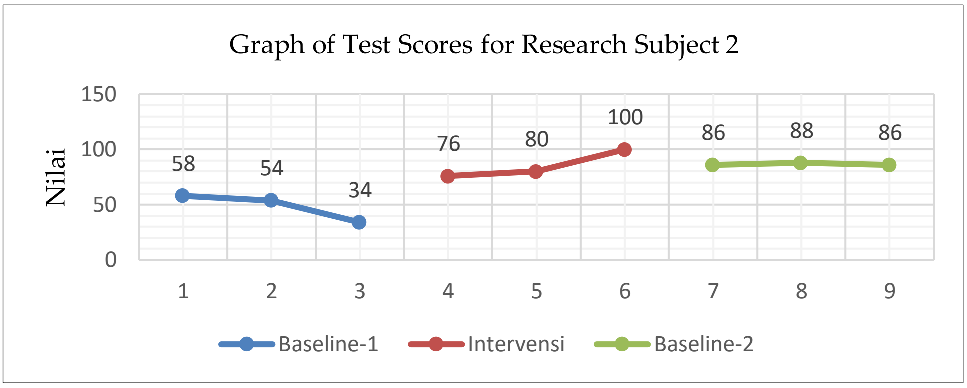

Figure 2. Spatial Ability Scores Across Sessions for Subject 2

As shown in Figure 3, Subject 3 began with moderate baseline performance yet still exhibited clear separation between baseline and intervention phases. Although a slight reduction occurred in A2 relative to peak intervention scores, maintenance remained substantially above baseline. Replication of improvement patterns across subjects with varying initial competence strengthens internal validity and aligns with methodological recommendations emphasizing replication as a core principle in single-case experimental research (Travers et al., 2026).

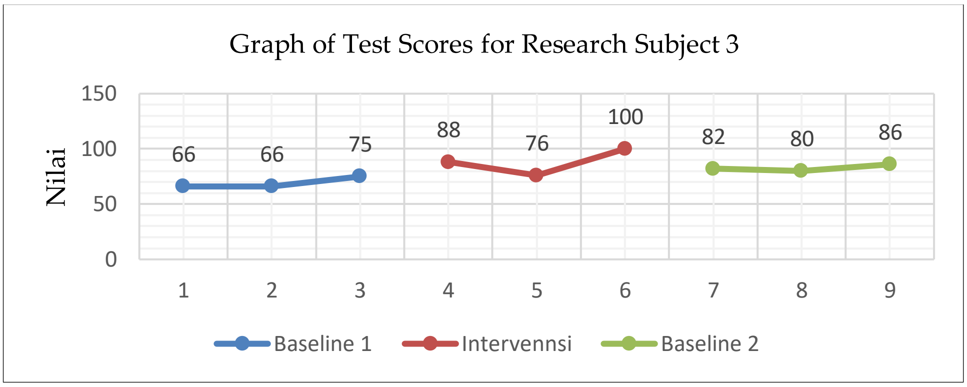

Figure 3. Spatial Ability Scores Across Sessions for Subject 3

Beyond overall level change, examination of each spatial indicator reveals differentiated patterns of improvement. Spatial orientation improved markedly in tasks requiring identification of hidden cube faces and relative positioning within composite structures. During baseline, students frequently relied on guessing strategies, whereas during intervention, students actively manipulated AR models to verify structural relationships before responding. This shift reflects enhanced representational fluency—the ability to coordinate external visual representations with internal mental models—which is central to geometry cognition.

Spatial visualization, particularly in tasks involving cube nets, showed progressive strengthening across intervention sessions. The AR-based textbook offered dynamic transformations from net to solid, making abstract processes more concrete. This made it easier to build schemas and lessened the cognitive load. Spatial transformation and mental rotation also improved consistently, as repeated interaction with manipulable 3D objects supported the transition from external manipulation to internal visualization.

Maintenance of performance during A2 indicates that improvements were not merely temporary novelty effects but reflect internalized spatial schemas. In single-case logic, sustained improvement after withdrawal strengthens the argument for genuine cognitive change rather than short-term engagement (Aldawoud, 2025).

Within the context of deaf education, these findings carry particular significance. Deaf learners predominantly process information visually (Blatto-Vallee et al., 2007). Instruction that lacks visual clarity may limit conceptual understanding. The AR-based textbook addressed this need by transforming abstract geometric relationships into observable and manipulable forms. Observational data further revealed increased autonomy, with students independently exploring models and using visual or sign-supported explanations to describe spatial relationships. This was also supported by interview data. One student said, "It's easier to understand the material because I can see and move the object directly," and another said, "I don't have to guess anymore because I can see the shape clearly." These responses indicate improved conceptual understanding and reduced reliance on guess-based reasoning.

Questionnaire responses indicated highly positive perceptions across clarity, engagement, and usefulness dimensions, with mean scores exceeding 4.0 on a 5-point scale. This suggests that students consistently perceived the AR-based learning environment as clear, engaging, and beneficial for understanding geometry concepts. This positive perception aligns with observed increases in student engagement during intervention sessions, where active interaction with AR models appeared to sustain attention and motivation. Such findings are consistent with previous research indicating that interactive, technology-enhanced learning environments can improve students’ motivation and attitudes toward mathematics (Elmalı & Çıtak, 2026; Nisa, 2019).

The convergence of quantitative SSR indicators—baseline stability, zero overlap, positive trend direction, maintenance effects, and strong NAP values—with qualitative observations and student perceptions strengthens the credibility of the findings through methodological triangulation (Creswell & Creswell, 2018). Collectively, these results provide empirical evidence that the AR-based mathematics textbook effectively enhances mathematical spatial ability among deaf students. The integration of dynamic visualization, embodied interaction, and individualized SSR analysis offers strong support for the use of augmented reality in inclusive mathematics education.

Conclusions and Suggestions

This study concludes that the Augmented Reality (AR)-based mathematics textbook was effective in improving the mathematical spatial ability of deaf students in geometry learning, particularly in cube and rectangular prism topics. Using a Single

Subject Research (A1–B–A2) design, effectiveness was demonstrated through stable baseline performance, immediate level changes during intervention, consistent upward trends, zero overlap between baseline and intervention data, and maintenance of improvement during the withdrawal phase. These patterns across three participants indicate a functional relationship between AR-supported instruction and enhanced spatial orientation, visualization, transformation, and representation skills.

Qualitative findings further revealed positive learning experiences. Students reported greater clarity, engagement, and confidence, while observations showed increased autonomy and active manipulation of three-dimensional models. The convergence of quantitative and qualitative evidence suggests that improvements reflected meaningful conceptual development rather than procedural familiarity.

Theoretically, this study contributes to spatial reasoning research within deaf education by demonstrating that dynamic and manipulable visual representations can facilitate internalization of spatial processes for visually oriented learners. Methodologically, the integration of AR-based instruction within an SSR framework highlights the value of individualized intervention analysis in special education contexts.

However, the study involved only three participants within a limited time frame. Future research should include larger samples, extended intervention periods, and diverse educational settings to examine long-term and generalizable effects. Overall, the findings support the pedagogical value of AR in fostering inclusive and accessible geometry learning.

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References

Aldawoud, A. A. (2025). Visual analysis of single-case experimental design data for graduate students of special education. *Acta Psychologica*, *261*(April), 105950. https://doi.org/10.1016/j.actpsy.2025.105950

Alqahtani, A. A. (2025). Teachers' obstacles and supports in distance learning education for students who are deaf and hard of hearing in the Kingdom of Saudi Arabia. *Research in Developmental Disabilities*, *164*(July), 105086. https://doi.org/10.1016/j.ridd.2025.105086

Anwar, R., Elbashir, A. M., Magdy, R., Ahmad, Z., & Al-Thani, N. J. (2024). Effectiveness of STEM based workshop for deaf education: Exploratory study. *Heliyon*, *10*(16), e36012. https://doi.org/10.1016/j.heliyon.2024.e36012

Azuma, R. T. (1997). A survey of augmented reality. *Presence: Teleoperators and Virtual Environments*, *6*(4), 355–385. https://doi.org/10.1162/pres.1997.6.4.355

Blatto-Vallee, G., Kelly, R. R., Gaustad, M. G., Porter, J., & Fonzi, J. (2007). Visual-spatial representation in mathematical problem solving by deaf and hearing students. *Journal of Deaf Studies and Deaf Education*, *12*(4), 432–448. https://doi.org/10.1093/deafed/enm022

Bond, M., Buntins, K., Bedenlier, S., Zawacki-Richter, O., & Kerres, M. (2020). Mapping research in student engagement and educational technology in higher education: a systematic evidence map. *International Journal of Educational Technology in Higher Education*, *17*(1). https://doi.org/10.1186/s41239-019-0176-8

Buliali, J., Nurlaelah, E., & Dahlan, J. A. (2021). Augmented Reality Based Geometry Learning Media to Improve Students' Spatial Ability. *Journal of Physics: Conference Series*, *1806*(1), 12034. https://doi.org/10.1088/1742-6596/1806/1/012034

Chen, L., & Wang, Y. (2022). Mathematics anxiety and mathematical calculation in deaf children: A moderated mediation model of mathematics self-efficacy and intelligence. *Research in Developmental Disabilities*, *120*(February 2021), 104125. https://doi.org/10.1016/j.ridd.2021.104125

Creswell, J. W., & Creswell, J. D. (2018). *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches* (M. O'Hrffernan (ed.); Fifth). SAGE Publication. https://doi.org/10.4324/9780429469237-3

Elmalı, F., & Çıtak, H. (2026). Design, Development, and Formative Evaluation of a Tablet-Based Augmented Reality Application for Early Number Learning. *International Journal of Human-Computer Interaction*, *0*(0), 1–21. https://doi.org/10.1080/10447318.2026.2622591

Garzón, J., Kinshuk, Baldiris, S., Gutiérrez, J., & Pavón, J. (2020). How do pedagogical approaches affect the impact of augmented reality on education? A meta-analysis and research synthesis. *Educational Research Review*, *31*(July 2019), 100334. https://doi.org/10.1016/j.edurev.2020.100334

Isharyadi, R., & Herman, T. (2022). Designing learning material assisted by augmented reality to improve spatial thinking skills. *Al-Jabar: Jurnal Pendidikan Matematika*, *13*(2), 413–422. https://doi.org/10.24042/ajpm.v13i2.15242

Kaufmann, H., & Schmalstieg, D. (2003). Mathematics and geometry education with collaborative augmented reality. *Computers and Graphics (Pergamon)*, *27*(3), 339–345. https://doi.org/10.1016/S0097-8493(03)00028-1

Kaźmierczak, R., Grunwald, G., Skowroński, R., Kaźmierczak, L., & Kowalczyk, C. (2025). Augmented reality tools for mathematics and geoscience education. *Scientific Reports*, *15*(1), 1–16. https://doi.org/10.1038/s41598-025-02090-z

Koparan, T., Dinar, H., Koparan, E. T., & Haldan, Z. S. (2023). Integrating augmented reality into mathematics teaching and learning and examining its effectiveness. *Thinking Skills and Creativity*, *47*(June 2022), 101245. https://doi.org/10.1016/j.tsc.2023.101245

Linn, M. C., & Petersen, A. C. (1985). Emergence and characterization of sex differences in spatial ability: A meta-analysis. *Child Development*, *56*(6), 1479–1498.

Lu, H., Fan, Z., Leung, F. K. S., Chen, X., & Zuo, H. (2026). How is spatial reasoning associated with mathematical ability? Evidence based on a meta-analysis. *Learning and Individual Differences*, *125*(June 2025). https://doi.org/10.1016/j.lindif.2025.102838

Nisa, M. (2019). Pengaruh Pengalaman Belajar Terhadap Sikap Positif Siswa Dalam Pembelajaran Matematika di SMP NU Dukuhjati Krangkeng-Indramayu. *Pediamatika: Journal of Mathematical Science and Mathematics Education*, *1*(1), 145–155.

Otálora, Y., & Taborda-Osorio, H. (2025). Contributions of numeral knowledge, spatial reasoning, and numerical mapping to first graders' arithmetic and geometric skills. *Cognitive Development*, *73*(November 2024). https://doi.org/10.1016/j.cogdev.2024.101520

Prahmana, R. C. I. (2021). *Desain Penelitian Pendidikan Matematika*. Deepublish.

Su, S., Han, J., Dong, F., & Chen, J. (2025). The priming of visual picture cues on onomatopoeic processing of reduced-hearing students: An empirical study. *Acta Psychologica*, *258*(July), 105259. https://doi.org/10.1016/j.actpsy.2025.105259

Tang, E., & Wong, T. T. Y. (2026). Potential underlying mechanisms of spatial-mathematical associations among primary school children. *Journal of Experimental Child Psychology*, *261*(September 2025), 106369. https://doi.org/10.1016/j.jecp.2025.106369

Thom, J. S., & Weber, J. C. (2026). Exploring Deaf Aesthetics as Spatial-Geometric Thinking, Acting, and Feeling: A Case Study. *Education Sciences*, *16*(1), 88. https://doi.org/10.3390/educsci16010088

Travers, J. C., Tincani, M., Dowdy, A., Forbes, H., & Johnson, J. V. (2026). A Registered Report on Selective Reporting in Single-Case Experimental Research. *Remedial and Special Education*, *47*(1), 36–52. https://doi.org/10.1177/07419325251350697

Weigand, H. G., Hollebrands, K., & Maschietto, M. (2025). Geometry education at secondary level – a systematic literature review. *ZDM - Mathematics Education*, *57*(4), 829–843. https://doi.org/10.1007/s11858-025-01703-1

Yang, Y., Du, W., Mavrikis, M., & Geraniou, E. (2026). Spatial Skill Development Through Augmented Reality in Mathematics Education: A Scoping Review. In *Digital Experiences in Mathematics Education* (Issue 0123456789). Springer International Publishing. https://doi.org/10.1007/s40751-025-00187-8

Zapata, M., Ramos-Galarza, C., Valencia-Aragón, K., & Guachi, L. (2024). Enhancing mathematics learning with 3D augmented reality escape room. *International Journal of Educational Research Open*, *7*(October). https://doi.org/10.1016/j.ijedro.2024.100389

Zou, N., Wang, R., Chai, C., & Zhang, X. (2025). Spatial adventure: An augmented reality system for children's spatial skills training. *International Journal of Child-Computer Interaction*, *46*(September), 100783. https://doi.org/10.1016/j.ijcci.2025.100783