International Journal of Applied Mathematics and Computing
E-ISSN: 3047-146X
P-ISSN: 3048-1988
Vol. 3 No. 2 April 2026

Research Article

Supporting Junior Secondary Students' Geometric Visualisation Through Augmented Reality and a STAR Scaffold: An Exploratory Pre–Post Pilot Study

Dinda Ayu Putri[1]*, Bulan Ainayya Fathiyyaturahma[2], Liffia Salwa Nabila[3]

[1] Muhammadiyah 3 Sukolilo Junior High School, Pati, Indonesia; widiagustini37@gmail.com
[2] Muhammadiyah 3 Sukolilo Junior High School, Pati, Indonesia; bullbbin@gmail.com123
[3] Muhammadiyah 3 Sukolilo Junior High School, Pati, Indonesia; liffia.s.n17@gmail.com
*Corresponding author: widiagustini37@gmail.com

Abstract. Geometric visualisation is a fundamental yet challenging competency in mathematics education, particularly for junior secondary school students who struggle to interpret three-dimensional (3D) spatial structures using conventional two-dimensional instructional media. This study examines the effectiveness of Augmented Reality (AR) integrated with the STAR instructional strategy (Situation, Task, Action, Result) in enhancing students' geometric visualisation skills. A quantitative pilot study employing a one-group pretest–posttest design was conducted with 9 eighth-grade students at SMP Muhammadiyah 3 Sukolilo, Indonesia, selected through purposive sampling. Data were collected using validated geometry visualisation tests administered before and after the intervention. The data were analysed using normalised gain (N-Gain) and paired sample t-test. The results indicate a significant improvement in students' performance, with the mean score increasing from 20.00 (SD not reported due to small sample size) on the pretest to 88.89 on the posttest. The normalised gain score ($g = 0.67$) indicates a moderate-to-high improvement, while inferential analysis shows statistically significant differences ($p < 0.05$). The findings suggest that AR enhances spatial cognition by enabling interactive manipulation of 3D geometric objects, while the STAR strategy provides structured cognitive scaffolding that guides students through contextual problem understanding, task execution, and reflective learning. The novelty of this study lies in integrating STAR as a structured pedagogical scaffold within an AR-based spatial learning environment for geometry instruction in a low-resource classroom context. This study contributes to the growing body of evidence supporting immersive technologies in mathematics education, particularly for improving spatial reasoning in early secondary learners.

Keywords: Augmented Reality; Geometric Visualization; Junior Secondary Education; Spatial Reasoning; STAR scaffold.

Received: March 02th, 2026
Revised: March 30th, 2026
Accepted: April 29th, 2026
Published: April 30th, 2026
Curr. Ver.: April 30th, 2026

1. Introduction

Spatial reasoning and visualisation are foundational components of mathematical thinking because students are required to interpret, construct, manipulate, and transform representations of objects and relationships that are not always directly observable. These abilities are particularly important in three-dimensional geometry, where learners must coordinate multiple viewpoints, recognise visible and hidden elements, mentally rotate objects, construct and evaluate nets, and connect two-dimensional diagrams with three-dimensional structures. Although external visualisations can support mathematical understanding, their effectiveness depends not merely on their visual appeal but on how learners interpret, manipulate, and integrate them into mathematical reasoning processes.[1][2].

Three-dimensional geometry remains a challenging topic for many junior secondary students. Conventional instruction often relies on textbook illustrations, board drawings, and static two-dimensional diagrams. These representations are useful for introducing geometric concepts and are relatively easy to implement in ordinary classrooms. However, their limitations become apparent when students are expected to imagine object rotation, inspect hidden faces or edges, compare alternative viewpoints, and determine whether a two-dimensional net can be folded into a valid three-dimensional solid. Previous instructional approaches have therefore attempted to strengthen students' spatial understanding through physical manipulatives, dynamic geometry software, virtual environments, and augmented reality. Physical models provide tangible experiences but may be limited in flexibility and availability. Dynamic and virtual representations allow manipulation and repeated exploration, but they may require adequate digital infrastructure and careful pedagogical guidance. Augmented reality offers an additional advantage by overlaying virtual three-dimensional objects onto the learner's physical environment, thereby enabling students to inspect, rotate, and interact with geometric objects through mobile devices[3].

The need to strengthen mathematical reasoning is also evident in the Indonesian educational context. In the Programme for International Student Assessment PISA 2022, Indonesian students obtained an average mathematics score of 366, compared with the OECD average of 472, and only 18% of Indonesian students reached at least Level 2 proficiency[4]. Although PISA does not directly measure geometric visualisation, these results indicate persistent difficulties in applying mathematical representations, reasoning, and problem-solving strategies in unfamiliar contexts. Such difficulties are relevant to geometry learning, especially when students are required to move beyond routine recognition of shapes and engage in representational transformation, spatial interpretation, and mathematical justification.

Preliminary classroom observations and diagnostic activities at SMP Muhammadiyah 3 Sukolilo indicated that Grade 8 students experienced difficulties in identifying geometric elements from alternative viewpoints, selecting valid cube nets, interpreting projections, and imagining rotations of three-dimensional objects. Instruction in the observed classroom had mainly depended on textbook diagrams and teacher drawings on the board. While these conventional representations are important, they may not provide sufficient opportunities for students to manipulate objects, examine occluded features, or coordinate multiple perspectives. This situation suggests a need for an instructional design that combines visual–spatial interaction with structured problem-solving guidance.

Augmented reality has been increasingly investigated as a promising tool for supporting geometry learning. By placing virtual objects in real-world contexts, AR can make abstract geometric structures more accessible and interactive. Meta-analytic evidence indicates that AR can improve educational outcomes, although its effects vary according to intervention duration, subject area, learner characteristics, and instructional design quality[5]. Studies in mathematics and geometry education have reported that AR-based learning can enhance students' three-dimensional thinking, spatial perception, and engagement when learners can rotate, inspect, and manipulate virtual solids[3][6]. The strength of AR lies in its capacity to provide interactive and embodied visualisation experiences that are difficult to achieve through static diagrams alone.

Nevertheless, AR is not automatically effective. Technology by itself does not determine what learners should observe, what actions they should perform, or how visual exploration should be translated into mathematical conclusions. Recent reviews of AR in mathematics education have noted that some studies emphasise technological affordances more than subject-specific pedagogy, while learning processes, contextual factors, and measurement procedures are often insufficiently documented[7]. As a result, the effectiveness of AR-based geometry learning remains dependent on how the technology is integrated into a coherent instructional sequence. This limitation points to the importance of scaffolding students' interaction with AR so that exploration becomes purposeful, conceptually focused, and connected to mathematical reasoning.

To address this issue, the present study integrates mobile augmented reality with a four-stage STAR scaffold consisting of Situation, Task, Action, and Result. In this study, STAR is not positioned as an established theory of geometry learning but as a practical problem-solving scaffold. The Situation stage introduces students to a spatial problem context; the Task stage clarifies the expected mathematical goal; the Action stage guides students to manipulate and inspect AR objects purposefully; and the Result stage requires students to articulate their conclusions based on the preceding exploration. This design is expected to bridge the gap between interactive visualization and mathematical reasoning by providing both technological affordance and instructional structure.

This study focuses on Grade 8 students at SMP Muhammadiyah 3 Sukolilo and examines the feasibility of implementing an AR-STAR learning sequence in a small, intact junior secondary classroom within a resource-constrained school setting. Given the pre-experimental design, the study does not claim to establish definitive causal effectiveness. Instead, it investigates whether the intervention can be implemented in the classroom and whether the observed pre–post changes in students' geometry performance and self-reported geometric visualisation are sufficiently promising to justify a larger controlled study.

The study contributes to the literature in three ways. First, it provides empirical evidence on the implementation of mobile AR for three-dimensional geometry learning in an Indonesian junior secondary school context. Second, it proposes and examines the use of the STAR scaffold as a structured sequence for guiding students' AR-based spatial exploration. Third, it offers preliminary evidence and methodological reflections that may inform future controlled studies on AR-supported geometry instruction, particularly in schools with limited resources. Based on these considerations, the study addressed the following research questions: RQ1. How did students' geometry performance scores change from before to after the AR-STAR learning sequence? RQ2. How did students' self-reported geometric visualisation change from before to after the learning sequence? RQ3. What implementation observations and measurement limitations should inform a subsequent controlled study?

The remainder of this paper is organised as follows. The next section presents the research method, including the research design, participants, intervention procedure, instruments, and data analysis. The results section reports students' pre–post performance, changes in self-reported geometric visualisation, and implementation observations. The discussion section interprets the findings in relation to previous studies, theoretical considerations, and the limitations of the pre-experimental design. The final section concludes the paper and offers recommendations for future controlled investigations.

2. Literature Review

Geometric Visualisation and Spatial Reasoning

Geometric visualisation involves creating, interpreting, and transforming internal and external representations of spatial objects. It overlaps with, but is not identical to, general visual imagery. Spatial reasoning includes awareness of positions and relations, mental rotation, spatial orientation, and the ability to use spatial information in problem solving. These abilities are strongly connected to mathematics learning and are trainable rather than fixed traits[8].

In school geometry, visualisation is both a learning process and an assessable product. Learners may need to recognise a solid from a projection, infer an unseen edge, construct or evaluate a net, or justify how a cross-section changes with the cutting plane. A high-quality assessment should therefore distinguish recognition, description, construction, transformation, and application. The present study's questionnaire attempted to cover visual, verbal, drawing, logical, and applied dimensions; however, these dimensions were measured through self-report rather than direct performance, so they should be interpreted as students' perceived competence rather than verified spatial ability.

Educational Affordances and Constraints of Augmented Reality

AR can co-locate a virtual model with the physical learning environment, permit real-time changes of viewpoint, and support embodied interaction through device movement and touch gestures. These affordances are relevant to geometry because they externalise spatial transformations that students might otherwise need to perform mentally. Research on AR-supported solid geometry has reported positive learning and usability outcomes among secondary students (Lin et al., 2015), while AR geometry tutorials have been associated with stronger three-dimensional thinking [3].

The instructional benefits of AR are not automatic. Three-dimensional visualisations can direct attention to spatial relations, but they can also impose interaction demands, split attention, or encourage superficial exploration. Krüger et al. (2022)[9] found that 3D AR representations supported spatial-relation learning, while also showing that learners' prior spatial ability can moderate benefits. Broader meta-analytic evidence similarly indicates positive average outcomes alongside substantial heterogeneity and a need for careful instructional design[5]. These findings justify pairing AR with prompts that make the learner's objective and actions explicit.

The STAR Scaffold as an Instructional Sequence

The STAR sequence used in this study comprised four operational stages. Situation introduced a contextualised geometric problem and identified the relevant solid. Task clarified what the learner needed to determine, such as identifying a hidden diagonal, selecting a valid net, or predicting a cross-section. Action prompted deliberate manipulation, including rotation, zooming, viewpoint changes, and comparison with a two-dimensional representation. The result required the learner to state, draw, or select a conclusion and relate it to the observed evidence.

This sequence was intended to prevent unstructured technology use. It resembles general problem-solving scaffolds in that it separates problem interpretation, goal identification, strategic action, and evaluation. Nevertheless, STAR has not yet been validated as a distinct instructional model for geometry. Accordingly, the present study treats the scaffold as a design feature whose independent contribution cannot be separated from the AR component in a single-group combined intervention.

Research Gap and Provisional Contribution

Recent reviews identify growing global interest in AR for spatial skill development, particularly in primary and junior secondary geometry, but also emphasise inconsistent findings, limited documentation of learning processes, and weaknesses in measurement sensitivity [7]. The present pilot responds to this gap at a modest scale by documenting an explicit AR-supported problem-solving sequence, reporting participant-level change transparently, and reframing the evidence as preliminary rather than causal. Its main contribution is therefore methodological and design-oriented: it identifies a promising intervention configuration and the revisions required before a confirmatory study can be conducted.

3. Method

Design

The study used a one-group pretest–posttest pilot design. All participants completed baseline measures, received the combined AR-STAR learning sequence, and completed the same outcome formats after the intervention. This design is appropriate for early feasibility work but is vulnerable to testing, maturation, history, expectancy, and novelty effects; therefore, changes cannot be attributed uniquely to the intervention (Shadish et al., 2002).

Setting and Participants

The study was conducted during the second semester of the 2025/2026 academic year at SMP Muhammadiyah 3 Sukolilo, Pati Regency, Central Java, Indonesia. Participants were the entire Grade 8 cohort (N = 9). Because all eligible students in the cohort participated, the procedure is more accurately described as an intact-cohort census than purposive sampling. Participant names were removed from the analytic dataset and replaced with identification codes P1–P9. Demographic variables were not reported in the source manuscript and should be added in a future study where ethically appropriate.

Learning Environment and Intervention

The AR materials were developed and delivered through Assemblr EDU and accessed using Android smartphones. The learning objects represented three-dimensional solids and allowed students to rotate, enlarge, and inspect models from multiple viewpoints. Printed geometry materials and a QR code or marker provided access to the digital objects. The intervention followed the four-stage sequence summarised in Table 1. The exact number of sessions, minutes per session, teacher prompts, and student-to-device ratio were not recorded in sufficient detail in the source manuscript; these details must be documented before journal submission because intervention dosage and fidelity are essential for replication.

Table 1. Operationalisation of the AR-STAR learning sequence.

Stage	Instructional purpose	Student activity	AR interaction
Situation	Orient attention to a spatial problem	Identify the solid, given information, and relevant viewpoint	Open the model and position it in the physical environment
Task	Specify the target of reasoning	State what must be identified, predicted, drawn, or justified	Select the relevant object or view
Action	Support purposeful spatial exploration	Rotate, zoom, compare views, inspect faces/edges, and test a conjecture	Use touch gestures and device movement to manipulate the 3D model
Result	Convert exploration into mathematical output	Record an answer, drawing, classification, or explanation	Return from manipulation to the worksheet or assessment prompt

Measures

Geometry performance test

The direct performance outcome was a five-item multiple-choice test scored from 0 to 100 in 20-point increments. Items addressed recognition of cross-sections, identification of a solid from verbal properties, and interpretation of orthographic views. In the source instrument, two items were duplicated, which reduces content coverage and threatens validity. The test should therefore be treated as a brief researcher-developed achievement probe rather than a validated measure of geometric visualisation. A future study should use parallel pretest and posttest forms, expert content validation, item analysis, and reliability evidence.

Self-report visualisation questionnaire

The secondary outcome was a 20-item questionnaire using a four-point response scale (1 = strongly disagree to 4 = strongly agree). Four items represented each of five intended domains: visual recognition, verbal description, drawing, logical reasoning, and application. The total score was expressed as the mean of the 20 items. Because the measure asks students to judge what they believe they can do, it assesses perceived competence rather than observed visualisation performance. The small sample was inadequate for a defensible psychometric evaluation, and the restricted posttest variance makes reliability estimates unstable.

Implementation observations

Classroom observations documented whether the AR model loaded, whether the marker or surface was detected under normal lighting, whether rotation and zoom functions operated, and whether the available Android devices could run the material. These observations were descriptive and were not collected with a validated usability scale.

Procedure

Students first completed the geometry performance test and self-report questionnaire. The teacher or research team then introduced the AR interface and demonstrated how to open, rotate, enlarge, and inspect the solids. Students worked through geometry activities organised by the STAR prompts and subsequently completed post-intervention measures. The original documentation does not report the exact interval between pretest and posttest, whether the assessment items were reordered, or whether students received corrective feedback before posttesting. These procedural details should be specified in any submitted version.

Data Analysis

Descriptive statistics were calculated for pretest, posttest, and change scores. Normalised gain was computed as g = (post − pre)/(maximum score − pre). For transparency, both the gain calculated from the class means and the mean of participant-level gains were examined; these values differ slightly for the questionnaire because the normalised gain is nonlinear. With only nine participants, normality tests have limited diagnostic value. Change scores for the performance test were strongly non-normal and showed ceiling compression, so the exact Wilcoxon signed-rank test was emphasised. Paired-samples t tests, mean-difference confidence intervals, and Cohen's dz were reported as sensitivity analyses rather than as the sole basis for inference. Statistical significance was evaluated at alpha = .05, but estimates and design limitations were given greater interpretive weight than p values.

4. Result and Discussion

Implementation Feasibility

The first objective of this study was to examine whether the AR-STAR learning sequence could be implemented in a real junior secondary classroom setting with limited technological resources. The intervention was implemented using mobile augmented reality materials designed to display three-dimensional geometry objects, particularly cube-related representations such as solids, faces, edges, vertices, rotations, projections, and nets. The learning sequence followed the four STAR stages: Situation, Task, Action, and Result. At the Situation stage, students were introduced to a geometry problem context. At the Task stage, they identified the mathematical goal to be solved. At the Action stage, they manipulated AR objects through rotation, zooming, and viewpoint changes. At the Result stage, students formulated their answers based on the visual exploration.

The AR materials were accessed through Android smartphones available during the classroom session. The application successfully displayed three-dimensional objects, and the rotation and zoom functions operated during implementation. Surface or marker detection also worked under normal classroom lighting, indicating that the intervention did not require highly specialised laboratory conditions. Most of the available Android smartphones were compatible with the AR materials, suggesting that mobile AR may be technically feasible in ordinary school environments where students or teachers have access to basic smartphones.

However, the evidence for feasibility should be interpreted with caution. The study did not collect a standardised usability score, such as the System Usability Scale, nor did it record interaction log data, dropout information, time-on-task data, or a formal fidelity checklist. Therefore, the implementation evidence is limited to classroom observation and researcher notes. This means that the present study can only claim basic technical and instructional feasibility, not full usability validation. Future studies should include usability questionnaires, device compatibility records, classroom observation rubrics, screen recordings, and fidelity checklists to determine whether the AR-STAR intervention is implemented consistently across students and sessions.

Table 2. summarises the implementation components observed during the AR-STAR learning sequence.

Component	Observation	Interpretation
Device	Android smartphones were used during learning	Feasible with commonly available mobile devices
AR display	Three-dimensional objects appeared successfully	Basic AR object rendering was functional
Interaction	Rotation and zoom functions worked during classroom use	Students could inspect objects from different viewpoints
Detection	Markers or surfaces were detected under normal classroom lighting	No special lighting condition was required
Compatibility	Most available Android smartphones could run the materials	Potentially suitable for resource-constrained classrooms
Limitation	No usability score, log data, or fidelity checklist was collected	Feasibility evidence remains preliminary

The feasibility findings are important because the intervention was designed not only as a technology-enhanced activity but also as a pedagogically guided learning sequence. The successful operation of the AR materials allowed students to perform the intended visual-spatial actions required in the STAR scaffold. In this sense, the technical feasibility supported the instructional feasibility of the intervention. Nevertheless, without systematic usability and fidelity data, it remains unclear whether all students experienced the intervention in the same way or whether some learning gains were influenced by novelty, peer assistance, or repeated exposure to similar test items.

Data Source and Evaluation Measures

The dataset consisted of pretest and posttest scores from a small intact class of Grade 8 students at SMP Muhammadiyah 3 Sukolilo. Two types of data were collected: geometry performance scores and self-reported geometric visualisation scores. The geometry performance test consisted of five items related to three-dimensional geometry. The self-reported geometric visualisation questionnaire used a four-point scale to capture students' perceived ability to imagine, rotate, inspect, and interpret geometric objects.

Because the study used a one-group pretest–posttest design with a very small sample, the analysis focused on descriptive statistics, mean differences, confidence intervals, exact non-parametric testing, paired-samples sensitivity analysis, and normalised gain. The Wilcoxon signed-rank test was emphasised because the sample was small, the change scores were not normally distributed, and posttest scores clustered near the maximum. The paired-samples t test was reported only as a sensitivity analysis, not as the primary basis for inference.

The normalised gain was used to estimate the proportion of possible improvement achieved by students. It was calculated using the following formula:

$$g = \frac{Posttes - Pretest}{Maximum\ Score - Pretest}$$

For class-level gain, the formula was:

$$gClass = \frac{Posttes - Pretest}{Maximum\ Score - Pretest} x100\%$$

The normalised gain was interpreted using conventional categories

Normalised Gain	Interpretation
$g < 0.30$	Low gain
$0.30 \le g < 0.70$	Moderate gain
$g \ge 0.70$	High gain

These evaluation measures were used to determine whether the pre–post pattern was sufficiently promising to justify a larger controlled study. However, because the design did not include a comparison group, the results should not be interpreted as definitive causal evidence

Table 3. Participant-level pretest and posttest scores (de-identified).

ID	Performance pre	Performance post	Individual g	Self-report pre	Self-report post	Individual g
P1	0	80	0.80	2.60	3.25	0.46
P2	60	100	1.00	1.00	3.25	0.75
P3	0	80	0.80	2.40	3.30	0.56
P4	20	100	1.00	2.45	3.30	0.55
P5	0	80	0.80	1.50	3.30	0.72
P6	0	80	0.80	1.25	3.30	0.75
P7	40	100	1.00	1.90	3.25	0.64
P8	60	100	1.00	1.70	3.60	0.83
P9	0	80	0.80	2.40	3.25	0.53

To complement the participant-level data, Table 3 summarises the aggregate pre–post outcomes, including mean scores, standard deviations, mean changes, confidence intervals, Wilcoxon test results, paired-samples t-test results, and class-level normalised gain.

Table 4. Summary of pre and post–outcomes.

Outcome	Pre M (SD)	Post M (SD)	Mean change	95% CI	Exact Wilcoxon p	Paired t	Class-level g
Performance (0–100)	20.00 (26.46)	88.89 (10.54)	68.89	55.33–82.45	.0039	t(8)=11.72, p<.001	0.86
Self-report (1–4)	1.91 (0.58)	3.31 (0.11)	1.40	0.93–1.87	.0039	t(8)=6.89, p<.001	0.67

Geometry Performance

The geometry performance scores increased for every participant after the AR-STAR learning sequence. The mean score rose from 20.00 before the intervention to 88.89 after the intervention. The standard deviation decreased from 26.46 at pretest to 10.54 at posttest, indicating that students' scores became more clustered at a higher performance level after the learning sequence. The mean increase was 68.89 points, with a 95% confidence interval of [55.33, 82.45].

Table 5. Descriptive statistics of geometry performance.

Measure	Pretest	Posttest	Mean Difference
Mean	20.00	88.89	68.89
Standard Deviation	26.46	10.54	—
95% CI of Mean Difference	—	—	[55.33, 82.45]
Wilcoxon Signed-Rank Test	—	—	W = 0, p = .0039
Paired-Samples t Test	—	—	t(8) = 11.72, p < .001
Cohen's dz	—	—	3.91
Class-Mean Normalised Gain	—	—	0.86
Mean Individual Normalised Gain	—	—	0.89

The exact Wilcoxon signed-rank test showed a statistically significant increase in performance scores, W = 0, p = .0039. This result indicates that the posttest scores were consistently higher than the pretest scores across participants. A paired-samples t test also indicated a significant increase, t(8) = 11.72, p < .001, with Cohen's dz = 3.91. However, the effect size should be interpreted with caution. In a very small sample, standardised effect sizes can be inflated, especially when the test consists of only a few items and when posttest scores approach the maximum possible score.

The normalised gain results further support the positive pre–post pattern. The class-mean normalised gain was 0.86, while the mean participant-level gain was 0.89. Both values fall within the high-gain category. This suggests that, on average, students achieved a large proportion of the possible improvement available to them. From an instructional perspective, the improvement may be related to the combined role of AR visualisation and STAR scaffolding. AR allowed students to inspect three-dimensional objects dynamically, while the STAR scaffold directed their attention toward specific problem-solving actions. In conventional instruction, students often depend on static diagrams and must mentally infer rotations, hidden faces, or alternative viewpoints. In the AR-STAR sequence, these spatial transformations became more accessible because students could manipulate virtual objects directly and then connect their observations to the required mathematical task.

Nevertheless, the findings should not be interpreted as proof that AR-STAR alone caused the improvement. Several alternative explanations remain possible. First, students may have benefited from repeated testing because the pretest and posttest measured similar constructs. Second, the five-item scale was relatively coarse, making large score changes more likely when students moved from very low initial performance to correct responses after instruction. Third, the posttest scores were clustered near the maximum, suggesting a possible ceiling effect. Fourth, because there was no control group, the study cannot rule out the influence of teacher support, classroom interaction, peer assistance, or short-term practice effects. Therefore, the geometry performance result is best interpreted as promising preliminary evidence. The result supports the feasibility and potential usefulness of AR-STAR for learning three-dimensional geometry, but it does not yet establish causal effectiveness.

Self-Reported Geometric Visualisation

Students' self-reported geometric visualisation also increased after the AR-STAR learning sequence. The questionnaire mean rose from 1.91 to 3.31 on a four-point scale. The standard deviation decreased from 0.58 to 0.11, indicating that students' responses became more consistently positive after the intervention. All participants reported higher scores after the learning sequence. The mean increase was 1.40 points, with a 95% confidence interval of [0.93, 1.87].

Table 6. Descriptive statistics of self-reported geometric visualisatio.

Measure	Pretest	Posttest	Mean Difference
Mean	1.91	3.31	1.40
Standard Deviation	0.58	0.11	—
95% CI of Mean Difference	—	—	[0.93, 1.87]
Wilcoxon Signed-Rank Test	—	—	W = 0, p = .0039
Paired-Samples t Test	—	—	t(8) = 6.89, p < .001
Cohen's dz	—	—	2.30
Class-Mean Normalised Gain	—	—	0.67
Mean Individual Normalised Gain	—	—	0.64

The exact Wilcoxon signed-rank test indicated a significant increase in self-reported visualisation, $W = 0$, $p = .0039$. The paired-samples t test produced a similar conclusion, $t(8) = 6.89$, $p < .001$, with Cohen's dz = 2.30. The class-mean normalised gain was 0.67, while the mean individual normalised gain was 0.64. These values fall within the moderate-to-high range.

This result suggests that students perceived themselves as more capable of visualising geometric objects after engaging with the AR-STAR sequence. The increase may be explained by the affordances of AR, which enabled students to rotate, zoom, and view objects from different perspectives. These actions may have helped students connect visual experience with self-confidence in spatial reasoning. The STAR scaffold may also have contributed by making the learning process more structured. Rather than exploring AR objects randomly, students were guided to identify the problem situation, clarify the task, perform relevant actions, and formulate a result.

However, the very narrow posttest spread suggests that the questionnaire may have been affected by a ceiling effect or response-shift effect. A ceiling effect may have occurred because many students selected high scores after the intervention, leaving little room for variation. A response-shift effect may also have occurred if students' understanding of geometric visualisation changed after the learning experience, causing them to reinterpret the questionnaire items differently at posttest. Furthermore, because the measure was self-reported, the result reflects students' perceived ability rather than direct evidence of spatial reasoning competence.

For this reason, future studies should combine self-report questionnaires with performance-based spatial visualisation tasks, interviews, screen recordings, or think-aloud protocols. Such triangulation would make it possible to determine whether students' increased confidence corresponds to improved spatial reasoning processes.

5. Discussion

Principal Findings

This pilot study examined the feasibility and short-term learning pattern of an AR-STAR learning sequence for three-dimensional geometry in a Grade 8 classroom. The results showed a consistent within-group improvement: all nine students obtained higher geometry performance scores and higher self-reported geometric visualisation scores after the intervention. The largest descriptive change occurred in the five-item geometry performance test, while self-reported visualisation also increased substantially. In addition, the AR materials were technically stable enough for students to display, rotate, zoom, and inspect virtual three-dimensional solids during classroom use.

These findings suggest that the AR-STAR learning sequence was feasible in the observed classroom context and that the intervention was associated with promising short-term gains. The result is educationally meaningful because the students' initial performance indicated difficulty in interpreting three-dimensional objects from static two-dimensional representations. After participating in the AR-STAR sequence, students appeared better able to identify, manipulate, and reason about geometric objects. The combination of interactive AR visualisation and explicit problem-solving prompts may therefore offer a practical way to support spatial reasoning in resource-constrained school settings.

However, the findings should not be interpreted as definitive evidence that AR-STAR caused the improvement. The study used a one-group pretest–posttest design, so the observed gains cannot be separated from repeated exposure to similar items, short-term memory, teacher guidance, peer interaction, novelty effects, or increased classroom attention. The highly compressed posttest scores also suggest a ceiling effect, indicating that the instruments may have been insufficiently sensitive to distinguish moderate from advanced performance after instruction. Thus, the appropriate conclusion is that AR-STAR was feasible and associated with promising short-term improvement in this small cohort, rather than that it was conclusively effective for junior secondary geometry learning in general.

The principal finding is therefore twofold. First, the intervention was technically and instructionally implementable in a real classroom using available mobile devices. Second, the pattern of pre–post improvement justifies further development and more rigorous testing. A larger controlled study is needed to determine whether AR-STAR produces learning gains beyond conventional instruction, AR without scaffolding, or other forms of visual support.

Interpretation in Relation to Previous Research — Revised

The observed improvement is consistent with recent literature suggesting that augmented reality can support mathematics learning by making abstract and spatially demanding concepts more visible, manipulable, and interactive. A systematic review by Herwayuninda Annisa dan Muhtarom[10] found that AR has been widely applied in mathematics education, particularly in geometry-related topics, and that most reviewed studies reported positive learning outcomes. However, the review also noted that AR implementation requires careful attention to pedagogical design, classroom context, and technical constraints. This supports the interpretation that the AR component in the present study may have helped students inspect geometric objects more directly, especially when dealing with cube nets, rotations, projections, and multiple viewpoints.

The present findings are also aligned with studies showing that AR becomes more educationally meaningful when it is combined with instructional guidance rather than used only as a visualisation tool. Uriarte-Portillo et al[11], for example, developed an intelligent AR-based geometry learning system and found that students using AR with additional tutoring support achieved higher learning gains than students using AR alone. Similarly, Tarng et al[12], reported that a mobile AR learning system improved geometric understanding and reduced cognitive load when compared with traditional learning materials. These studies suggest that the value of AR lies not simply in presenting three-dimensional objects, but in structuring students' interaction with these objects.

In this study, the STAR sequence may have functioned as a simple pedagogical scaffold that directed students' attention from problem context to task clarification, object manipulation, and result articulation. This is important because students may not automatically transform visual exploration into mathematical reasoning. Without guiding prompts, AR-based activities may remain visually engaging but conceptually shallow. The STAR stages were therefore intended to help students use AR models purposefully: students first identified the situation, clarified the task, manipulated the virtual object, and then explained the result.

This interpretation is supported by broader work on visualisation and spatial reasoning in mathematics education. Lowrie and Logan[13], showed that spatial visualisation can support mathematical learning, particularly when spatial tools are embedded within mathematics lessons rather than treated as isolated activities. Harris[14] also argues that spatial reasoning should be understood within meaningful educational contexts, not only through decontextualised psychometric tests. These perspectives strengthen the rationale for integrating AR visualisation with mathematical tasks and classroom-based reasoning.

Nevertheless, the present study cannot determine whether the observed improvement resulted from AR, the STAR scaffold, teacher assistance, repeated testing, or the interaction among these factors. Yang et al[15], similarly note that findings in AR-supported spatial learning remain difficult to compare because studies differ in tool design, learning activities, intervention duration, contextual variables, and measurement sensitivity. The current pilot shares several of these limitations, particularly the use of a brief performance test, a self-report questionnaire, and a one-group pretest–posttest design. Therefore, the results should be

interpreted as preliminary evidence that informs a more rigorous follow-up study rather than as conclusive evidence of effectiveness.

Comparison with State-of-the-Art

Recent state-of-the-art studies show that augmented reality has been increasingly applied in mathematics education, especially in geometry-related topics, because it can support visualization, interactivity, motivation, geometric understanding, and spatial reasoning[10], [5], [16], [17], [15]. However, the literature also indicates that AR is not automatically effective. Its educational value depends on pedagogical design, student interaction, usability, classroom context, and the sensitivity of assessment instruments[15][18].

Compared with previous AR-based geometry studies, the present study has a more limited methodological scope but a specific instructional contribution. Studies such as Uriarte-Portillo et al.[19] and Tarng et al [5] used stronger comparative designs and showed that AR becomes more useful when it is supported by appropriate instructional guidance or learning design. In the present study, this guidance was provided through the STAR sequence: Situation, Task, Action, and Result. The sequence was intended to help students use AR objects purposefully, moving from problem understanding to object manipulation and mathematical explanation.

The present study is also related to recent works emphasising active learning and spatial reasoning in AR-supported mathematics. Volioti et al [16] Highlight AR as a tool for active mathematics learning, while Mandala et al. [17] and Rohendi et al. [15] show that AR-based geometry activities can support spatial reasoning and student interactivity. The present study extends this direction by integrating mobile AR with a simple scaffold that directly guides students' spatial exploration.

Therefore, the contribution of this study should be understood as feasibility-oriented rather than confirmatory. It provides preliminary evidence that mobile AR combined with STAR scaffolding can be implemented in a small Indonesian junior secondary classroom and can produce promising short-term pre–post changes. However, larger controlled studies with validated instruments, usability evaluation, and delayed posttesting are needed before stronger claims about effectiveness can be made.

Pedagogical Implications

For classroom practice, the findings suggest that low-cost mobile AR can be integrated into geometry lessons without requiring specialized head-mounted equipment or laboratory infrastructure. In this study, Android smartphones were sufficient to display and manipulate three-dimensional objects. This implication is consistent with recent studies showing that mobile AR can provide accessible and interactive learning environments for mathematics, particularly when the application is designed with clear instructional goals, simple navigation, and usable interfaces[16][20]. Therefore, mobile AR may be a realistic option for schools with limited resources, provided that the application is technically stable, compatible with available devices, and supported by teacher guidance.

The results also imply that AR should not be used as a passive visualization tool. Teachers should avoid activities that merely ask students to "look at the model." Instead, AR activities should include prompts that require students to predict, rotate, compare, identify hidden elements, justify their reasoning, and explain their conclusions. For example, before rotating a cube, students may be asked to predict which face will become visible. After rotating the object, students can compare their prediction with the AR display and explain the reason for any difference. Such prompts can help students connect visual manipulation with mathematical reasoning. This is important because recent AR-based mathematics studies emphasize that visualization becomes more meaningful when students are actively involved in solving tasks, experimenting with representations, and interpreting mathematical relationships[21][17].

The STAR scaffold may offer a simple structure for guiding this process. Through the Situation, Task, Action, and Result stages, students are encouraged to move from contextual understanding to purposeful manipulation and then to mathematical explanation. This structure may reduce unproductive exploration and help students use AR objects as reasoning tools rather than as visual attractions. The importance of this guidance is supported by studies showing that AR can increase student interactivity and positive responses in geometry learning when classroom activities are designed to promote active participation, manipulation, and explanation[22]. Thus, the pedagogical value of AR depends not only on the availability of three-dimensional digital objects, but also on how teachers organize students' attention, actions, and mathematical discourse.

AR should also complement rather than replace traditional mathematical representations. Students still need to draw diagrams, construct nets, use mathematical language, and provide verbal or written justification. Effective geometry learning requires students to move between multiple representational forms, including the physical classroom environment, virtual AR objects, two-dimensional diagrams, symbolic notation, and mathematical explanation. Recent work on GeoGebra augmented reality also suggests that AR can support mathematical problem solving when students are guided to connect dynamic visualization with conceptual interpretation and written reasoning[19]. Therefore, AR should be positioned as part of a broader representational ecology, not as a substitute for mathematical thinking

Implementation also requires attention to practical classroom conditions. Device compatibility, battery life, lighting, internet access, classroom movement, and shared-device arrangements can influence the quality of learning. If students share devices, teachers should ensure equitable participation so that each student has opportunities to manipulate the AR object, make predictions, observe spatial changes, and explain conclusions. In addition, usability evaluation should be included in future implementation because students' ability to benefit from AR depends partly on whether the application is easy to operate and whether its interface supports learning rather than distracting from it[23].

Finally, teachers need sufficient preparation to integrate AR meaningfully into mathematics instruction. Teacher preparation should include not only technical training on how to operate the AR application, but also pedagogical training on how to design prompts, manage classroom interaction, connect AR models to curriculum objectives, and assess students' reasoning. Recent reviews of AR in mathematics education highlight that teacher readiness, pedagogical design, and technical support remain important conditions for successful AR implementation[18]. Therefore, future AR-STAR implementation should include teacher orientation, lesson scenarios, student worksheets, observation checklists, and reflection activities to ensure that AR-based learning remains mathematically focused and instructionally coherent

Limitations and Priorities for a Confirmatory Study

This pilot study has several substantial limitations. First, the sample size was very small, with only nine participants. Such a sample provides unstable estimates and does not allow meaningful generalisation to a wider student population. Second, the absence of a comparison group prevents causal attribution. In a one-group pretest–posttest design, observed gains may be influenced by repeated testing, maturation, history, regression to the mean, short-term memory, teacher support, novelty effects, or other classroom factors rather than the intervention alone[24]. Therefore, it is not possible to determine whether the observed gains were caused specifically by AR-STAR, ordinary instruction, repeated exposure to similar items, or the interaction among these factors.

Third, the intervention duration, instructional dosage, and fidelity of implementation were not documented in sufficient detail. Without systematic fidelity evidence, it is difficult to determine whether all students experienced the same learning sequence or whether the intervention was implemented exactly as intended. Implementation fidelity is important because it helps researchers understand whether outcomes are related to the intended intervention, variations in delivery, or inconsistencies in implementation[25]. Fourth, the five-item geometry performance test was too brief and included a duplicated item. The strong posttest ceiling effect indicates that the test could not adequately distinguish students who achieved basic understanding from those who developed more advanced spatial reasoning.

Fifth, the self-reported geometric visualisation questionnaire measured students' perceived ability rather than their demonstrated spatial competence. Although self-report data are useful for capturing students' confidence and perceived visualisation ability, they may be affected by response bias or social desirability, especially when students complete the questionnaire immediately after a learning activity[26]. Therefore, self-report measures should be triangulated with performance-based spatial tasks, interviews, think-aloud protocols, student work analysis, or screen-recorded interaction data. Sixth, the same testing context may have increased practice effects or social desirability bias. Students may have responded more positively after the intervention because they knew what was expected or because they wanted to show appreciation for the learning activity.

Seventh, the study did not report sufficient demographic and contextual variables, such as prior mathematics achievement, gender distribution, access to digital devices, previous experience with AR, socioeconomic background, or teacher-related effects. These variables may influence how students interact with AR and how much they benefit from it. Finally, because the participants were minors, ethics approval, parental consent, student assent, anonymity, and data protection procedures should be clearly documented in the final manuscript. Reporting guidelines for pilot and feasibility studies emphasize the importance of transparent documentation of participant recruitment, consent procedures, intervention delivery, feasibility outcomes, and progression criteria for future definitive studies[27].

A confirmatory follow-up study should address these limitations through a stronger research design. First, the study should conduct an a priori power analysis to determine the minimum sample size. Second, it should recruit multiple classes and preferably multiple schools to improve generalizability. Third, it should include at least one active control group, such as conventional instruction with static diagrams, dynamic geometry software, or AR without STAR scaffolding. Fourth, it should use validated spatial reasoning and geometry instruments, preferably with parallel pretest and posttest forms to reduce testing effects.

Future studies should also document intervention dosage, teacher training, classroom implementation, and fidelity using observation rubrics or fidelity checklists. Delayed posttesting should be included to examine whether learning gains persist beyond immediate practice. Depending on the design, ANCOVA, multilevel modelling, or mixed-effects models may be more appropriate than simple pre–post tests because these approaches can adjust for baseline differences and classroom clustering. Qualitative data, such as student interviews, classroom observations, student worksheets, and AR interaction records, should also be used to understand how students interact with virtual objects and how visual exploration is transformed into mathematical reasoning.

In summary, this pilot provides cautious but useful evidence that AR-STAR is feasible and potentially valuable for supporting three-dimensional geometry learning. Its main contribution is not to prove definitive effectiveness, but to identify a promising instructional design, clarify implementation issues, and inform the design of a larger controlled study.

6. Conclusion

This study investigated the feasibility and preliminary learning pattern of an AR-STAR learning sequence for supporting Grade 8 students' three-dimensional geometry learning. The results showed that the intervention could be implemented in the observed classroom context using available Android smartphones. The AR materials successfully displayed three-dimensional objects, and students were able to rotate, zoom, and inspect virtual solids during the learning activities. These findings indicate that mobile AR can be technically feasible for geometry learning in a resource-constrained junior secondary school setting.

The study also found consistent pre–post improvement in both geometry performance and self-reported geometric visualisation. All nine students obtained higher scores after the AR-STAR learning sequence. The mean geometry performance score increased from 20.00 to 88.89, while the self-reported geometric visualisation score increased from 1.91 to 3.31 on a four-point scale. These results suggest that the combination of interactive AR visualisation and STAR scaffolding was associated with promising short-term gains in students' ability to engage with three-dimensional geometry tasks.

The findings support the main purpose of the study, namely, to explore whether AR supported by a structured pedagogical sequence could help students interact more meaningfully with spatial representations. The STAR stages—Situation, Task, Action, and Result—provided a simple structure for guiding students from problem recognition to purposeful manipulation and mathematical conclusion. In this sense, the study contributes to AR-based mathematics education by showing that AR should not be treated merely as a visual display technology, but should be integrated with instructional prompts that direct students' attention, actions, and reasoning.

The contribution of this study is modest but specific. It provides preliminary classroom-based evidence from an Indonesian junior secondary school context, highlights the potential of mobile AR for three-dimensional geometry learning, and proposes AR-STAR as a feasible instructional configuration for guiding students' spatial exploration. The study also offers methodological lessons for future research, particularly regarding the need for stronger instruments, usability evaluation, fidelity documentation, and controlled comparison.

However, the findings should be interpreted with caution. The study involved only nine students and used a one-group pretest–posttest design without a control group. Therefore, the observed gains cannot be attributed solely to the AR-STAR intervention. Repeated testing, teacher assistance, peer interaction, novelty effects, and short-term practice may also have contributed to the results. In addition, the performance test was brief and showed ceiling effects, while the self-report questionnaire measured perceived rather than demonstrated spatial competence.

Future studies should examine AR-STAR using a larger sample, multiple classes or schools, validated geometry and spatial reasoning instruments, parallel pretest and posttest forms, usability measures, and delayed posttesting. A controlled design comparing AR-STAR with conventional instruction, AR without STAR scaffolding, or other dynamic visualization tools would provide stronger evidence of effectiveness. Future research should also document intervention dosage, classroom implementation fidelity, teacher guidance, and students' interaction with AR objects. Such improvements would allow a more rigorous evaluation of whether AR-STAR can produce sustainable and transferable gains in geometry learning.

In conclusion, this pilot study does not establish definitive causal effectiveness, but it provides cautious and useful evidence that mobile AR combined with STAR scaffolding is feasible and potentially valuable for supporting three-dimensional geometry learning. The findings justify further development and confirmatory investigation of AR-STAR as a structured approach to integrating augmented reality into mathematics education

Author Contributions: Conceptualization, Dinda Ayu Putri, Bulan Ainayya Fathiyyaturahma, and Liffia Salwa Nabila; methodology, Dinda Ayu Putri and Bulan Ainayya Fathiyyaturahma; software, not applicable; validation, Dinda Ayu Putri, Bulan Ainayya Fathiyyaturahma, and Liffia Salwa Nabila; formal analysis, Dinda Ayu Putri and Liffia Salwa Nabila; investigation, Dinda Ayu Putri, Bulan Ainayya Fathiyyaturahma, and Liffia Salwa Nabila; resources, Dinda Ayu Putri, Bulan Ainayya Fathiyyaturahma, and Liffia Salwa Nabila; data curation, Bulan Ainayya Fathiyyaturahma and Liffia Salwa Nabila; writing—original draft preparation, Dinda Ayu Putri, Bulan Ainayya Fathiyyaturahma, and Liffia Salwa Nabila; writing—review and editing, Dinda Ayu Putri, Bulan Ainayya Fathiyyaturahma, and Liffia Salwa Nabila; visualization, Liffia Salwa Nabila; supervision, not applicable; project administration, Dinda Ayu Putri; funding acquisition, not applicable. All authors have read and agreed to the published version of the manuscript

Funding: This research received no external funding. The study was conducted as part of a junior secondary school competition proposal.

Data Availability Statement: The data supporting the findings of this study are not publicly available due to privacy and ethical considerations involving minor participants. De-identified data may be made available from the corresponding author upon reasonable request and with appropriate permission

Acknowledgements: The authors would like to express their sincere gratitude to the Principal of SMP Muhammadiyah 3 Sukolilo, Pati, Central Java, Indonesia, for the support, permission, and encouragement provided during the implementation of this study. The authors also thank the supervising teacher for the guidance, assistance, and constructive feedback throughout the preparation and implementation of the research. Appreciation is also extended to the mathematics teacher, school staff, and students who participated in the classroom activities. This study was conducted as part of a junior secondary school competition proposal. During the preparation of this manuscript, AI-based language assistance was used to support proofreading, language refinement, and academic editing. The authors reviewed, revised, and approved the final content of the manuscript and take full responsibility for its accuracy and integrity

Conflicts of Interest: The authors declare no conflict of interest. This research received no external funding; therefore, no funder had any role in the design of the study, in the collection, analysis, or interpretation of data, in the writing of the manuscript, or in the decision to publish the results

Referensi

[1] J. Schoenherr and S. Schukajlow, "Characterizing external visualization in mathematics education research : a scoping review," *ZDM – Math. Educ.*, vol. 56, no. 1, pp. 73–85, 2024, doi: 10.1007/s11858-023-01494-3.

[2] A. Arcavi, "The role of visual representations in the learning of mathematics," *Educ. Stud. Math.*, vol. 52, no. 3, pp. 215–241,

2003, doi: 10.1023/A:1024312321077.

[3] E. İbili, M. Çat, D. Resnyansky, S. Şahin, and M. Billinghurst, "An assessment of geometry teaching supported with augmented reality teaching materials to enhance students' 3D geometry thinking skills," *Int. J. Math. Educ. Sci. Technol.*, vol. 51, no. 2, pp. 224–246, Feb. 2020, doi: 10.1080/0020739X.2019.1583382.

[4] OECD, "PISA 2022 Results," Paris, 2023. doi: https://doi.org/10.1787/53f23881-en.

[5] H. Chang *et al.*, "Computers & Education Ten years of augmented reality in education : A meta-analysis of (quasi-) experimental studies to investigate the impact," *Comput. Educ.*, vol. 191, no. August, p. 104641, 2022, doi: 10.1016/j.compedu.2022.104641.

[6] H.-C. K. Lin, M.-C. Chen, and C.-K. Chang, "Assessing the effectiveness of learning solid geometry by using an augmented reality-assisted learning system," *Interact. Learn. Environ.*, vol. 23, no. 6, pp. 799–810, Nov. 2015, doi: 10.1080/10494820.2013.817435.

[7] Y. Yang, W. Du, M. Mavrikis, and E. Geraniou, "Spatial Skill Development Through Augmented Reality in Mathematics Education: A Scoping Review," *Digit. Exp. Math. Educ.*, 2025, doi: 10.1007/s40751-025-00187-8.

[8] D. H. Uttal *et al.*, "The malleability of spatial skills: a meta-analysis of training studies.," *Psychol. Bull.*, vol. 139, no. 2, pp. 352–402, Mar. 2013, doi: 10.1037/a0028446.

[9] J. M. Krüger, K. Palzer, and D. Bodemer, "Learning with augmented reality: Impact of dimensionality and spatial abilities," *Comput. Educ. Open*, vol. 3, p. 100065, 2022, doi: https://doi.org/10.1016/j.caeo.2021.100065.

[10] H. Annisa and I. Dwijayanti, "Impact of AR- s upported STEAM based project learning on students ' numeracy skills : A meta analytic," *Al-Jabar J. Pendidik. Mat.*, vol. 17, no. 01, pp. 323–337, 2026, doi: https://doi.org/10.24042/10.24042/ajpm.v17i1.30143.

[11] A. Uriarte-Portillo, R. Zatarain-Cabada, M. L. Barrón-Estrada, M. B. Ibáñez, and L.-M. González-Barrón, "Intelligent Augmented Reality for Learning Geometry," 2023. doi: 10.3390/info14040245.

[12] W. Tarng, J.-K. Huang, and K.-L. Ou, "Improving Elementary Students' Geometric Understanding Through Augmented Reality and Its Performance Evaluation," *Systems*, vol. 12, no. 11, p. 493, 2024, doi: 10.3390/systems12110493.

[13] T. Lowrie and T. Logan, "Spatial Visualization Supports Students' Math: Mechanisms for Spatial Transfer," 2023. doi: 10.3390/jintelligence11060127.

[14] D. Harris, "Spatial reasoning in context: bridging cognitive and educational perspectives of spatial-mathematics relations," *Front. Educ.*, vol. Volume 8, 2023, doi: 10.3389/feduc.2023.1302099.

[15] Y. Yang, W. Du, M. Mavrikis, and E. Geraniou, "Spatial Skill Development Through Augmented Reality in Mathematics Education : A Scoping Review," *Digit. Exp. Math. Educ.*, no. 0123456789, 2025, doi: 10.1007/s40751-025-00187-8.

[16] C. Volioti, C. Orovas, T. Sapounidis, G. Trachanas, and E. Keramopoulos, "Augmented Reality in Primary Education: An Active Learning Approach in Mathematics," *Computers*, vol. 12, no. 10, p. 207, 2023, doi: 10.3390/computers12100207.

[17] A. S. Mandala, L. Anwar, C. Sa, and H. Zulnaidi, "Development of mobile augmented reality-based geometry learning games to facilitate spatial reasoning," *Infin. J.*, vol. 14, no. 2, pp. 323–348, 2025, doi: https://doi.org/10.22460/infinity.v14i2.p323-348.

[18] N. Voulgari, M. Panagopoulos, and V. Garneli, "A systematic review of augmented reality in mathematics education: Fostering learning through art integration," *Arts Commun.*, vol. 3, no. 2, p. 4446, 2024, doi: https://doi.org/10.36922/ac.4446.

[19] M. U. Gusteti and W. Rahmalina, "GeoGebra Augmented Reality : An Innovation in Improving Students ' Mathematical Problem-Solving Skills To cite this article : GeoGebra Augmented Reality : An Innovation in Improving Students ' Mathematical Problem-Solving Skills," *Int. J. Educ. Math. Sci. Technol.*, vol. 13, no. 3, pp. 584–596, 2025, doi: https://doi.org/10.46328/ijemst.4872.

[20] N. I. N. Ahmad, S. N. Junaini, and S. K. Jali, "Enhancing Mathematics Learners' Experience using Mobile Augmented Reality: Conceptual Framework for the Design and Evaluation," *Int. J. Adv. Sci. Eng. Inf. Technol.*, vol. 13, no. 3 SE-Articles, pp. 1068–1079, Jun. 2023, doi: 10.18517/ijaseit.13.3.17112.

[21] Orlando Iparraguirre-Villanueva, Cleoge Paulino-Moreno, and Henry Chero-Valdivieso, "Integration of GeoGebra Calculator 3D with Augmented Reality in Mathematics Education for an Immersive Learning Experience," *Int. J. Eng. Pedagog.*, vol. 14, no.

3, pp. 92–107, 2024, doi: https://doi.org/10.3991/ijep.v14i3.47323.

[22] H. Rohendi, D., Ramadhan, M. O., Abdul Rahim, S. S., and Zulnaidi, "Enhancing student ' s interactivity and responses in learning geometry by using augmented reality," *EURASIA J Math Sci Tech Ed*, vol. 21, no. 1, 2025, doi: https://doi.org/10.29333/ejmste/15796.

[23] R. Chonchaiya and N. Srithammee, "Augmented Reality as a Tool for Enhancing Geometry Learning and Improving Mathematical Understanding," *ECTI Trans. Comput. Inf. Technol.*, vol. 19, no. 2 SE-Research Article, pp. 350–363, Apr. 2025, doi: 10.37936/ecti-cit.2025192.260291.

[24] E. Marsden and C. J. Torgerson, "Single group, pre- and post-test research designs: Some methodological concerns," *Oxford Rev. Educ.*, vol. 38, no. 5, pp. 583–616, Oct. 2012, doi: 10.1080/03054985.2012.731208.

[25] C. Carroll, M. Patterson, S. Wood, A. Booth, J. Rick, and S. Balain, "A conceptual framework for implementation fidelity," *Implement. Sci.*, vol. 2, no. 1, p. 40, 2007, doi: 10.1186/1748-5908-2-40.

[26] K. Lavidas, S. Papadakis, D. Manesis, A. S. Grigoriadou, and V. Gialamas, "The Effects of Social Desirability on Students' Self-Reports in Two Social Contexts: Lectures vs. Lectures and Lab Classes," *Information*, vol. 13, no. 10, p. 491, 2022, doi: 10.3390/info13100491.

[27] S. M. Eldridge *et al.*, "CONSORT 2010 statement: extension to randomised pilot and feasibility trials," *BMJ*, vol. 355, p. i5239, Oct. 2016, doi: 10.1136/bmj.i5239.