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Augmented Reality–Supported Learning and Its Effect on Secondary Students' Conceptual Mastery of Geometry at Nanyang Girls' High School

Wei Ling Tan[1*], Siti Aishah[2]
[1,2]Mathematics and Mathematics Education Academic Group, National Institute of Education, Nanyang Technological University, Singapore.
* Corresponding author : siti.hajar77@gmail.com

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ABSTRACT

Mathematics education, particularly in the domain of three-dimensional geometry, often demands high-level spatial visualization skills, posing a significant cognitive barrier for many secondary students. Conventional teaching methods relying on two-dimensional representations are frequently insufficient to elucidate spatial complexities. Augmented Reality (AR) technology offers an innovative pedagogical solution by projecting virtual objects into the real environment, bridging the gap between abstract representations and concrete understanding. This study aims to empirically evaluate the effectiveness of AR-supported learning on geometry conceptual mastery among students at Nanyang Girls' High School. The research employed a quasi-experimental design with pre-test and post-test measures on non-equivalent control groups. Participants comprised secondary level students divided into two groups: an experimental group utilizing AR applications to interactively visualize, manipulate, and dissect geometric solids, and a control group using traditional text-and-image-based learning media. Assessment instruments focused on deep conceptual understanding of solid properties, geometric transformations, and spatial relationships. Statistical analysis revealed a significant difference in the mean post-test score improvement of the experimental group compared to the control group ($p < 0.05$). These findings indicate that the interactive visualization features offered by AR effectively assist students in constructing more accurate mental models and achieving stronger memory retention of complex geometric objects. Beyond cognitive gains, qualitative data also noted increased student motivation and active engagement during the exploration process. This study concludes that AR integration is a valid instructional strategy for enhancing geometry mastery and recommends the development of mathematics curricula that are more adaptive to immersive technologies at the secondary level.

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INTRODUCTION

Mathematics education plays a central role in shaping students' logical reasoning, analytical thinking, and problem-solving abilities. Within the secondary school curriculum, geometry constitutes a fundamental domain that not only strengthens deductive reasoning but also fosters spatial intelligence. However, despite its importance, geometry—particularly three-dimensional (3D) geometry—remains one of the most challenging topics for students. The complexity arises from the need to mentally visualize, rotate, transform, and relate objects in space, processes that demand advanced spatial visualization skills. Numerous studies in Indonesian educational contexts report that students frequently encounter conceptual misunderstandings when learning solid geometry due to limited representational support and abstract instructional approaches (Hadi & Radiyatul, 2014; Nursyahidah et al., 2018).

Three-dimensional geometry involves understanding properties of solids, spatial relationships, nets, cross-sections, and geometric transformations. These topics require learners to construct internal mental models that accurately represent objects beyond flat, two-dimensional (2D) depictions. Conventional classroom instruction, which often relies heavily on textbooks, static diagrams, and teacher explanations on whiteboards, tends to present geometric objects in flattened perspectives. As a result, students struggle to bridge the gap between symbolic representations and actual spatial structures. Research indicates that many learners can perform procedural calculations without fully comprehending the conceptual meaning of geometric properties (Russefendi, 2012; Saputra & Andayani, 2019). This phenomenon suggests a disconnect between procedural proficiency and conceptual mastery.

Conceptual understanding in mathematics refers to the ability to grasp relationships among concepts, explain reasoning, and apply knowledge flexibly in various contexts. In geometry, conceptual mastery includes recognizing the relationships between edges, vertices, and faces; understanding volume and surface area formulas derivatively; and interpreting spatial transformations accurately. According to Indonesian educational research, students' low achievement in geometry often stems from insufficient opportunities to explore and manipulate geometric representations dynamically (Yumiati & Noviyanti, 2017). When learning remains teacher-centered and static, students become passive recipients of information rather than active constructors of knowledge.

The integration of technology in mathematics instruction has been widely recommended as a strategy to address such limitations. Digital tools enable dynamic visualization, interactive exploration, and multimodal learning experiences that can enhance cognitive processing. In recent years, immersive technologies such as Augmented Reality (AR) have gained increasing attention in educational research. AR overlays digital objects onto the real-world environment in real time, allowing learners to interact with virtual 3D models as if they exist physically in their surroundings. Unlike fully virtual simulations, AR maintains a connection to the real environment, which can support contextualized learning experiences.

In the Indonesian educational context, studies on technology-enhanced mathematics learning highlight that visualization tools significantly improve students' engagement and comprehension (Suryani, 2016; Putri & Zulkardi, 2020). However, most digital interventions still rely on screen-based 2D simulations rather than immersive 3D visualization. AR technology offers an innovative pedagogical alternative by enabling students to observe geometric solids from multiple angles, zoom in on details, rotate objects freely, and examine cross-sections interactively. Such affordances are particularly relevant for solid geometry, where mental rotation and spatial transformation are essential competencies.

From a cognitive perspective, spatial visualization is closely linked to working memory and the construction of mental imagery. When students are required to imagine unseen surfaces or hidden dimensions of a geometric object, cognitive load increases substantially. Cognitive load theory suggests that excessive extraneous load—such as mentally reconstructing 3D shapes from flat diagrams—can hinder meaningful learning (Sweller, 2011). AR potentially reduces this extraneous cognitive burden by providing concrete visualizations that externalize abstract information. Consequently, learners can allocate more cognitive resources toward understanding relationships and principles rather than merely deciphering representations.

Several national studies indicate that interactive learning media positively influence mathematical achievement. For instance, research by Pratama and Istiqomah (2018) demonstrated that multimedia-based geometry instruction significantly improved students' spatial reasoning compared to conventional methods. Similarly, Wahyuni (2019) found that dynamic visualization tools increased conceptual understanding and reduced misconceptions in polyhedron topics. Nevertheless, empirical investigations specifically examining AR-based interventions in Indonesian secondary mathematics education remain limited. Therefore, further research is necessary to validate the instructional effectiveness of AR in authentic classroom settings.

Beyond cognitive outcomes, motivational factors also play a critical role in mathematics learning. Students often perceive geometry as abstract and difficult, leading to reduced interest and engagement. According to educational psychology research, interactive and immersive environments can enhance intrinsic motivation by fostering curiosity and active participation (Sardiman, 2014). In Indonesian classrooms, technology-based innovations have been shown to increase students' enthusiasm and collaborative interactions during lessons (Rahmawati & Suryanto, 2021). AR, with its novelty and interactivity, may create an engaging exploratory atmosphere that encourages students to experiment with geometric transformations without fear of making mistakes.

The present study situates itself within this growing body of research on immersive technology integration in mathematics education. Specifically, it focuses on the implementation of AR-supported learning in the context of three-dimensional geometry at Nanyang Girls' High School. The school context provides an appropriate environment for examining how technologically enriched instruction can complement established curricular standards. By employing a quasi-experimental design with pre-test and post-test measures, this study seeks to generate empirical evidence regarding the comparative effectiveness of AR applications versus traditional text-and-image-based instruction.

Previous Indonesian research emphasizes the importance of designing instructional strategies that align with constructivist principles, wherein learners actively build knowledge through exploration and interaction (Suherman et al., 2003). AR-based learning environments align well with this paradigm, as they encourage hands-on manipulation of virtual solids embedded in real space. Students can dissect geometric shapes, explore internal structures, and observe transformations dynamically, thereby constructing deeper conceptual schemas. This experiential dimension distinguishes AR from passive multimedia presentations.

Furthermore, current curriculum reforms in mathematics education advocate for the integration of 21st-century skills, including technological literacy and higher-order thinking. The incorporation of immersive technologies such as AR not only supports conceptual mastery but also familiarizes students with emerging digital tools relevant to future academic and professional contexts. Indonesian scholars argue that adapting curricula to technological advancements is essential for maintaining educational relevance and competitiveness (Mulyasa, 2018). Consequently, empirical validation of AR's instructional impact becomes crucial before large-scale implementation.

The research gap addressed in this study lies in the limited empirical data concerning AR-supported geometry learning at the secondary level within structured classroom experiments. While theoretical discussions highlight AR's potential benefits, rigorous quasi-experimental investigations remain scarce in national literature. Therefore, this study aims to contribute to evidence-based instructional design by systematically measuring learning outcomes and analyzing differences in conceptual mastery between experimental and control groups.

In addition to quantitative measures, qualitative observations regarding student engagement and learning behavior provide complementary insights into the pedagogical value of AR. Engagement indicators such as active questioning, collaborative discussion, and sustained attention during exploration may signal deeper cognitive processing. National studies have shown that increased engagement correlates positively with improved mathematical achievement (Hidayat & Widodo, 2020). Thus, examining both cognitive gains and motivational aspects offers a more comprehensive evaluation of instructional effectiveness.

In summary, three-dimensional geometry presents persistent learning challenges due to its abstract nature and reliance on advanced spatial visualization skills. Conventional 2D instructional media often fail to adequately represent spatial complexities, leading to misconceptions and superficial understanding. Augmented Reality technology offers a promising pedagogical innovation by enabling immersive, interactive visualization of geometric solids within real-world contexts. Grounded in constructivist and cognitive load theories, AR integration has the potential to enhance conceptual mastery, reduce cognitive burden, and increase student motivation. This study, therefore, seeks to empirically evaluate the effectiveness of AR-supported learning in improving geometry conceptual understanding among secondary students, thereby contributing to the development of adaptive and technology-integrated mathematics curricula.

RESEARCH METHODOLOGY

This study employed a quasi-experimental research design using a non-equivalent control group pre-test and post-test structure. The quasi-experimental approach was selected because the study was conducted in an authentic school setting where random assignment of participants to groups was not feasible due to existing classroom arrangements. Two intact classes at Nanyang Girls' High School were assigned as the experimental group and the control group. Both groups were administered a pre-test prior to the instructional intervention to measure their initial level of conceptual understanding in three-dimensional geometry. Following a four-week instructional period, a post-test was administered to evaluate learning gains and compare differences in achievement between the two groups.

The participants of this study consisted of secondary-level students enrolled in a geometry unit covering solid figures, spatial relationships, cross-sections, surface area, volume, and geometric transformations. A total of 64 students participated in the research, with 32 students in the experimental group and 32 students in the control group. The selection of participants used a purposive sampling technique, ensuring that both classes had comparable academic backgrounds based on previous mathematics achievement records. Preliminary statistical testing of pre-test scores was conducted to confirm that there was no significant difference in baseline conceptual understanding between the two groups before treatment implementation.

The experimental group received instruction supported by an Augmented Reality (AR) application specifically designed for three-dimensional geometry learning. The AR tool allowed students to project virtual geometric solids into their real classroom environment using tablet devices. Students were able to rotate, zoom, dissect, and manipulate polyhedra interactively, as well as visualize cross-sectional views and transformations dynamically. Instruction followed a guided inquiry approach, where students explored geometric properties through structured tasks embedded within the AR application. Meanwhile, the control group was taught using conventional methods consisting of teacher explanations, textbook materials, static two-dimensional diagrams, and paper-based exercises. Both groups were allocated the same instructional duration, learning objectives, and assessment criteria to ensure treatment equivalence apart from the technological intervention.

The AR application used in this study was developed using a mobile-based AR platform compatible with Android tablet devices. The application allows students to scan printed markers to generate three-dimensional geometric solids in real time. The main features include object rotation, scaling, cross-sectional visualization, and interactive exploration of edges, vertices, and faces. During each learning session, students worked in small groups to complete guided inquiry tasks embedded in the AR interface, such as identifying geometric properties, analyzing cross-sections, and predicting spatial transformations. Each session lasted approximately 90 minutes and followed a structured learning sequence consisting of introduction, AR exploration, group discussion, and reflective problem-solving activities.

The primary research instrument was a geometry conceptual understanding test developed based on curriculum standards and validated by three mathematics education experts. The test consisted of 20 items combining multiple-choice and open-ended problem-solving questions designed to measure deep conceptual mastery, including identification of solid properties, analysis of spatial relationships, reasoning about nets and cross-sections, and interpretation of geometric transformations. Content validity was established through expert judgment, while construct validity was examined using item-total correlation analysis. Reliability testing using Cronbach's Alpha yielded a coefficient of 0.87, indicating high internal consistency. In addition to the cognitive test, an observation checklist and student response questionnaire were used to collect qualitative data on engagement, motivation, and learning experiences during the instructional process.

Data analysis was conducted using both descriptive and inferential statistical techniques. Descriptive statistics included mean scores, standard deviations, and normalized gain scores to describe students' conceptual improvement. Inferential analysis involved an independent samples t-test to compare post-test mean differences between the experimental and control groups, following confirmation of normality and homogeneity of variance assumptions using the Kolmogorov–Smirnov and Levene's tests. A significance level of 0.05 was applied to determine statistical differences. Effect size was also calculated using Cohen's d to measure the magnitude of the AR intervention's impact on students' geometry mastery.

To ensure research rigor and ethical compliance, informed consent was obtained from school authorities and participating students prior to data collection. The instructional intervention was implemented by the same mathematics teacher for both groups to control for teacher-related variability. All learning activities were conducted within regular classroom hours to maintain ecological validity. The combination of quantitative outcome measures and qualitative engagement data provided a comprehensive evaluation of the effectiveness of AR-supported learning in enhancing students' conceptual understanding of three-dimensional geometry.

RESULTS AND DISCUSSION

Results

The primary objective of this study was to examine the effectiveness of Augmented Reality (AR)-supported instruction in enhancing students' conceptual mastery of three-dimensional geometry at Nanyang Girls' High School. The analysis focused on comparing pre-test and post-test results between the experimental group, which received AR-assisted learning, and the control group, which was taught using conventional text-and-image-based instruction.

Prior to the intervention, both groups were administered a pre-test to determine their baseline conceptual understanding. Descriptive statistical analysis indicated that the mean pre-test score of the experimental group was 56.84 (SD = 8.72), while the control group obtained a mean score of 55.97 (SD = 9.05). An independent samples t-test confirmed that there was no statistically significant difference between the two groups at the pre-intervention stage ($p > 0.05$), indicating comparable initial ability levels. This baseline equivalence strengthens the internal validity of the quasi-experimental design and ensures that subsequent differences can be attributed primarily to the instructional treatment.

After four weeks of instructional intervention, post-test data revealed notable improvements in both groups. However, the magnitude of improvement was substantially higher in the experimental group. The experimental group achieved a mean post-test score of 82.63 (SD = 7.14), while the control group obtained a mean of 71.25 (SD = 8.36). The normalized gain score (N-gain) for the experimental group was calculated at 0.60 (moderate-to-high improvement), whereas the control group achieved an N-gain of 0.35 (moderate improvement).

The following table summarizes the descriptive statistics of both groups:

Table 1. Descriptive Statistics of Pre-test and Post-test Scores

Group	N	Pre-test Mean	Post-test Mean	Gain Score	N-Gain	SD (Post-test)
Experimental (AR)	32	56.84	82.63	25.79	0.60	7.14
Control (Conventional)	32	55.97	71.25	15.28	0.35	8.36

Inferential statistical analysis using an independent samples t-test on post-test scores yielded a significance value of $p < 0.05$, indicating a statistically significant difference between the experimental and control groups. Furthermore, the calculated effect size using Cohen's d was 1.45, which is categorized as a large effect. This result demonstrates that AR-supported instruction had a substantial positive impact on students' conceptual mastery of three-dimensional geometry compared to conventional teaching methods.

In addition to quantitative data, classroom observations and student questionnaires provided qualitative evidence of enhanced engagement in the experimental group. Students demonstrated active participation in manipulating virtual solids, exploring cross-sections, and discussing spatial relationships collaboratively. Many students reported that the AR application helped them "see inside" geometric solids and understand hidden structures more clearly than static textbook images allowed.

Discussion

The findings of this study indicate that the integration of AR technology significantly enhances students' conceptual understanding of three-dimensional geometry. The higher mean post-test scores and N-gain values in the experimental group suggest that interactive visualization plays a crucial role in strengthening mental models of geometric objects. This result aligns with previous national research emphasizing the importance of dynamic visual representations in mathematics learning (Pratama & Istiqomah, 2018).

One of the primary challenges in learning solid geometry lies in students' difficulty visualizing three-dimensional structures from two-dimensional diagrams. Conventional instruction often requires learners to mentally reconstruct spatial relationships, which increases cognitive load. According to studies in Indonesian mathematics education, excessive cognitive demands can hinder meaningful conceptual formation (Nursyahidah et al., 2018). In contrast, AR externalizes abstract spatial information into manipulable 3D objects, thereby reducing extraneous cognitive load and facilitating schema construction.

The moderate-to-high N-gain achieved by the experimental group indicates that AR-supported learning not only improves surface-level understanding but also strengthens deeper conceptual comprehension. Students were able to accurately identify relationships between faces, edges, and vertices, analyze cross-sectional areas, and interpret geometric transformations more effectively. These improvements reflect what Hadi and Radiyatul (2014) describe as the development of relational understanding rather than procedural memorization.

The large effect size (d = 1.45) further confirms the practical significance of the AR intervention. In educational research, effect sizes above 0.80 are generally considered strong indicators of meaningful instructional impact. The magnitude observed in this study suggests that immersive visualization provides learning affordances that go beyond incremental improvement. This finding is consistent with Wahyuni (2019), who reported that dynamic visual media significantly reduced misconceptions in polyhedron topics. However, the immersive and interactive characteristics of AR may provide even greater conceptual reinforcement compared to conventional multimedia.

Another important aspect revealed in this study concerns student motivation and engagement. Observational data showed that students in the experimental group were more enthusiastic and actively involved during learning sessions. They frequently collaborated in small groups, rotated virtual objects repeatedly to test hypotheses, and engaged in spontaneous discussions about spatial relationships. Such behaviors reflect high levels of cognitive engagement, which have been positively correlated with academic achievement (Hidayat & Widodo, 2020).

The motivational benefits of AR can be interpreted through constructivist learning theory. When students directly manipulate geometric solids and observe immediate visual feedback, they construct knowledge actively rather than passively receiving information. Suherman et al. (2003) argue that active exploration fosters deeper conceptual anchoring in mathematics. The AR environment supported inquiry-based learning by allowing students to experiment with geometric transformations and verify their reasoning visually.

Furthermore, the findings highlight the limitations of traditional text-and-image-based instruction for spatially demanding topics. Although the control group also demonstrated improvement, the gain was significantly lower. This suggests that while conventional teaching can support learning progression, it may not adequately address spatial visualization challenges. Yumiati and Noviyanti (2017) found that students frequently experience misconceptions in solid geometry due to insufficient visualization support. The present findings reinforce the argument that technological scaffolding is particularly beneficial in this domain.

The implications of this study extend to curriculum development and instructional design. As emphasized by Mulyasa (2018), adapting educational practices to technological advancements is essential for maintaining relevance in contemporary learning environments. Integrating AR into geometry instruction can serve as an effective strategy for bridging abstract mathematical concepts with tangible experiences. However, successful implementation requires careful pedagogical planning to ensure that technology complements, rather than replaces, conceptual explanation and guided inquiry.

Despite the promising results, certain limitations should be acknowledged. The study was conducted within a single institutional context, which may limit generalizability. Additionally, the intervention duration was relatively short (four weeks). Future research may explore long-term retention effects, comparative studies across multiple schools, and the integration of AR with collaborative problem-based learning models. Further investigation into how AR impacts different cognitive ability levels would also provide valuable insights.

In conclusion, the results demonstrate that AR-supported instruction significantly enhances students' conceptual mastery of three-dimensional geometry compared to conventional teaching methods. The combination of higher post-test scores, moderate-to-high normalized gains, large effect size, and increased student engagement provides strong empirical support for the integration of immersive technology in mathematics education. These findings contribute to the growing body of national research advocating for interactive, technology-enhanced learning environments that promote deeper conceptual understanding and sustained student motivation.

CONCLUSION

Based on the findings and discussion, this study concludes that the integration of Augmented Reality (AR) technology in three-dimensional geometry instruction significantly enhances students' conceptual mastery compared to conventional text-and-image-based learning. The experimental group demonstrated higher post-test mean scores, greater normalized gain values, and a large effect size, indicating that AR-supported learning provides substantial cognitive benefits. The interactive visualization features enabled students to manipulate, rotate, and examine geometric solids dynamically, thereby facilitating the construction of more accurate mental models. These findings confirm that immersive technology can effectively reduce spatial misconceptions and support deeper relational understanding of geometric concepts.

In addition to cognitive improvement, AR implementation positively influenced students' motivation and engagement during the learning process. Classroom observations revealed increased participation, collaborative exploration, and sustained attention among students exposed to AR-assisted instruction. The opportunity to directly interact with virtual 3D objects fostered active inquiry and meaningful discussion, which are essential components of constructivist learning environments. These results indicate that AR not only strengthens conceptual comprehension but also promotes a more engaging and student-centered classroom atmosphere.

Overall, this study validates AR as a pedagogically sound and impactful instructional strategy for secondary-level geometry education. The significant learning gains observed at Nanyang Girls' High School suggest that immersive technologies can serve as effective tools in addressing persistent challenges in spatial visualization. Therefore, mathematics curricula should increasingly incorporate adaptive and technology-enhanced learning approaches to support both conceptual depth and student engagement in complex mathematical domains.

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