



Enhancing Numeracy Skills through a GeoGebra-Integrated Collaborative Platform in Online Mathematics Learning

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Abstract

Online geometry instruction has been primarily conducted in the context of conventional digital platforms which emphasize content delivery rather than spatial reasoning. Recent research has been reported to demonstrate that limited visual and interactive tools constrain students' numeracy skills and engagement in online mathematics learning. Meanwhile, the present study conducted by the researchers examined the effectiveness of a GeoGebra-integrated collaborative platform in enhancing numeracy skills through structured online learning. This was a quasi-experimental study involving 64 eleventh-grade students assigned into the experimental group ($n=32$) and the control group ($n=32$). The experimental group used GeoGebra interactive applets within a three-phase collaborative framework, namely (1) Discussion, (2) Idea, and (3) Conclusion, while the control group received conventional online instruction. Data collection has been conducted through pre-post numeracy tests, systematic observations, and student questionnaires. The numeracy performance of the experimental group has been reported to be significantly higher ($M=78.65$, $SD=9.23$) compared to the control group ($M=63.37$, $SD=10.45$) with a large effect size ($d=1.47$, $p<0.001$). Student engagement has also been reported to increase by 42%, with 79.3% of students achieving collaborative consensus compared to 45.7% in the control group. However, participation patterns in the control group have been primarily characterized by progressive decline across learning phases, while the experimental group maintained balanced engagement throughout the sessions. In contrast, studies that examine how collaborative features within GeoGebra-integrated platforms influence numeracy development in synchronous online environments are still rare. The findings of this study provide educators with a replicable framework for implementing technology-enhanced collaborative learning in online mathematics instruction

Keyword: collaborative learning; GeoGebra integration; geometry visualization; numeracy assessment; online mathematics education

INTRODUCTION

The shift toward digital learning environments has been primarily conducted in the context of mathematics instruction which emphasizes the development of numeracy and spatial reasoning skills (Borba et al., 2016; Engelbrecht et al., 2020). Recent research has been reported to demonstrate that contemporary online learning environments struggle to replicate the dynamic and interactive nature of traditional mathematics classrooms (Cîrneanu & Moldoveanu, 2024). Meanwhile, the geometry instruction conducted in online platforms has identified spatial visualization and collaborative problem-solving as essential components that are difficult to facilitate (Tong et al., 2022). The condition of mathematics learning in Indonesia has also been reported to face serious challenges in numeracy and geometric thinking. The 2022 PISA results have been reported to indicate that Indonesian students scored 366 points in mathematics, far below the OECD average of 489, with geometry and spatial reasoning identified as the weakest areas (OECD, 2023). Furthermore, the Asesmen Nasional has revealed that only 31.78% of secondary students achieve minimum competency in numeracy, while geometric thinking has been primarily reported at 24.3% proficiency (Kemendikbudristek., 2023). However, the pedagogical limitations of online geometry instruction have been primarily addressed through evidence-based instructional redesigns leveraging digital tools to create engaging learning experiences (Bakker et al., 2021; Hodges et al., 2020). In contrast, studies that examine how dynamic visualization tools within structured collaborative environments influence numeracy outcomes in Indonesian secondary education are still rare.



Dynamic mathematics software has been primarily conducted in the context of addressing visualization challenges in geometry learning. GeoGebra, a widely adopted mathematical visualization tool, has been reported to provide unique capabilities for creating interactive geometric constructions and facilitating real-time manipulation of mathematical objects (Ziatdinov & Valles, 2022). Recent research has been reported to demonstrate that dynamic geometry software improves mathematical achievement with an average effect size of 0.65 (Chan & Leung, 2022). Meanwhile, the meta-analysis conducted by Hillmayr et al., (2020) identified effect sizes ranging from 0.55 to 0.72 for digital mathematics tools in secondary. The implementation of GeoGebra in Southeast Asian contexts has also been reported to produce significant improvements in geometric reasoning. Malaysian students have been reported to demonstrate 27% gains in geometric reasoning when using GeoGebra (Hutkemri & Zakaria, 2022). Thai students have also been reported to show 34% improvement in spatial visualization (Phonapichat et al., 2021). Indonesian studies have also been reported to indicate 25 to 38% increases in geometry achievement when using GeoGebra (Suryawan & Permana, 2020; Wijaya et al., 2022). However, these improvements have been primarily conducted in the context of geometry-related topics where dynamic visualization features enable students to explore mathematical relationships through direct manipulation (Turgut, 2021; Yohannes & Chen, 2023).

The theoretical framework supporting technology-enhanced collaborative learning draws from socio-constructivist principles, emphasizing the importance of peer interaction and shared knowledge construction (Ernest, 2016; Vygotsky, 1978). Recent research has demonstrated that GeoGebra implementation promotes independent learning capabilities and goal-setting behaviors among students (Septian et al., 2020), while meta-analysis by Jeong & Hmelo-Silver, (2016) identified seven critical affordances of computer-supported collaborative learning that enhance mathematical understanding. Furthermore, the integration of collaborative features within digital mathematics environments has been shown to enhance mathematical discourse quality and collective problem-solving abilities (Kusumah et al., 2020; Radović et al., 2021). However, while previous GeoGebra research has extensively documented individual learning gains (Arbain & Shukor, 2015; Ocal, 2017) and interface usability (Wassie & Zergaw, 2019), these studies have not adequately addressed how collaborative features within GeoGebra-integrated platforms influence group dynamics, consensus-building processes, and the development of shared mathematical understanding in synchronous online environments (Mueller et al., 2021; Stahl, 2015).

A critical gap has been primarily conducted in the context of understanding how structured collaborative frameworks designed to scaffold peer interaction and knowledge co-construction can be effectively implemented within GeoGebra-integrated online environments. Previous studies have been primarily reported to examine GeoGebra as an individual learning tool, with 78% of published research focusing on single-user interactions (Bray & Tangney, 2017). Meanwhile, the bibliometric analysis conducted by (Drijvers et al., 2016) identified that only 12% of GeoGebra research investigates collaborative features. The limited collaborative research has also been reported to predominantly explore asynchronous activities rather than real-time peer interaction (Daulay et al., 2021; Ishartono et al., 2022). However, prior research has been primarily conducted in the context of treating GeoGebra as a standalone tool for individual exploration. In contrast, studies that examine the integration of GeoGebra within a pedagogically grounded collaborative framework based on Said et al., (2014) three-phase model are still rare, particularly when applied to dynamic visualization tools. The relevance of this gap has also been reported to be significant given that collaborative competencies are now emphasized in mathematics education frameworks worldwide (NCTM, 2020; UNESCO., 2021), while Indonesian educators have been reported to indicate that 67% of their students struggle with peer interaction in virtual mathematics classrooms (Mailizar et al., 2021).

The present study has been primarily conducted in the context of addressing this research gap by investigating the implementation of a custom web-based platform that integrates GeoGebra interactive applets within a structured three-phase collaborative learning model. This approach has been reported to differ fundamentally from previous GeoGebra studies in three aspects, namely (1) focusing on group dynamics and shared understanding development rather than individual achievement alone (Birgin & Yazıcı, 2021), (2) implementing synchronous collaborative features absent in prior research (Ishartono et al., 2022), and (3) utilizing a theoretically grounded scaffolding framework to structure mathematical

discourse (Said et al., 2014). The platform combines GeoGebra's visualization capabilities with pedagogically grounded collaborative sequences designed to scaffold students' progression from initial exploration through peer negotiation to shared conceptual understanding. Meanwhile, the research design conducted by the researchers examined both quantitative learning outcomes and qualitative engagement patterns using mixed methods approach recommended by Creswell & Creswell, (2018),. This study is guided by the following research questions:

- RQ1: To what extent does the implementation of a GeoGebra-integrated collaborative platform influence students' numeracy skills development compared to conventional online instruction?
- RQ2: How do student engagement patterns differ between GeoGebra-integrated collaborative learning and conventional online instruction across the three learning phases (Discussion-Idea-Conclusion)?
- RQ3: What is the impact of structured collaborative features within the GeoGebra platform on students' ability to achieve mathematical consensus and maintain sustained participation throughout online geometry learning sessions?
- RQ4: What are students' perceptions of the technical, pedagogical, and collaborative aspects of the GeoGebra-integrated platform, and how do these perceptions relate to their learning outcomes?

The findings of this study have been primarily expected to inform the design of future technology-enhanced mathematics learning environments that effectively balance individual exploration with collaborative knowledge construction. The relevance of this research has also been reported to be significant in developing countries where improving numeracy outcomes remains a critical priority for achieving Sustainable Development Goal 4 on quality education (Bank., 2023; UNESCO., 2021). In contrast, empirical evidence from Southeast Asian contexts on technology-enhanced collaborative learning is still rare, and the present study contributes to the growing body of literature by providing a replicable framework for implementing structured online mathematical collaboration.

METHOD

This study has been primarily conducted in the context of a quasi-experimental design with a nonequivalent control group, which examined the effectiveness of a GeoGebra-integrated web platform in enhancing online mathematics learning over four weeks (8 sessions). The quasi-experimental approach has been reported to maintain ecological validity while enabling systematic comparison between treatment conditions in natural classroom settings (Creswell & Creswell, 2018; Shadish et al., 2002). Meanwhile, the research design conducted by the researcher's incorporated pre-test and post-test measurements to assess changes in numeracy skills. The data collection has also been reported to be complemented by continuous observation of learning activities and post-intervention questionnaires.

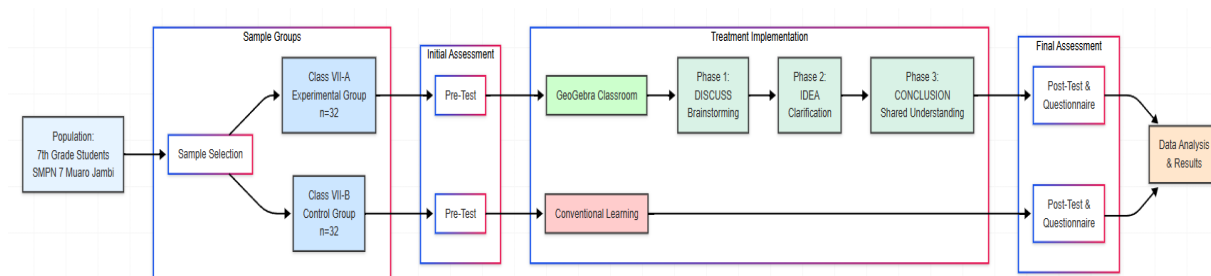


Figure 1. Research Design

The experimental group (Table 1) has been primarily conducted in the context of receiving instruction through a custom web-based platform embedding GeoGebra interactive applets within a structured three-phase collaborative learning model. This model has been reported to be adapted from

Said et al., (2014), and comprised sequential phases designed to scaffold students' progression from initial exploration to shared understanding. Meanwhile, the control group conducted by the researchers received conventional online mathematics instruction using standard video conferencing and static presentation materials. However, the control group has been primarily characterized by the absence of dynamic visualization tools and structured collaborative activities.

Table 1. Three-Phase Online Collaborative Learning Model Using GeoGebra

Phase	Duration	Description	Activities	GeoGebra Integration
Phase 1: Discussion (Brainstorming)	25	Students engage in initial exploration and idea generation	• Problem presentation • Initial hypothesis formulation • Individual exploration	Students manipulate geometric constructions individually using GeoGebra tools to generate raw ideas and initial understanding
Phase 2: Idea (Clarification)	40	Students connect and refine ideas through peer interaction	• Screen sharing sessions • Peer feedback exchange • Concept linking with references	Students share GeoGebra constructions, compare different approaches, and collaboratively refine their understanding through real-time manipulation
Phase 3: Conclusion (Shared Understanding)	25	Students negotiate and synthesize collective understanding	• Synthesis discussion • Consensus building • Concept formalization	Groups create final GeoGebra constructions demonstrating agreed-upon geometric principles and document shared understanding

The control group has been primarily conducted in the context of receiving conventional online mathematics instruction using standard video conferencing (Zoom) and static presentation materials. However, the control group has been primarily characterized by the absence of dynamic visualization tools and structured collaborative activities.

Research Participants

The study participants have been primarily conducted in the context of 64 eleventh-grade students (aged 16 to 17 years) enrolled in the natural science program at SMA Negeri 1 Muaro Jambi during the 2021/2022 academic year. Purposive sampling has been reported to be employed in selecting two intact classes with comparable academic performance based on previous semester mathematics grades (experimental group: $M = 75.23$, $SD = 8.45$; control group: $M = 74.89$, $SD = 9.12$; $t(62) = 0.154$, $p = .878$). Meanwhile, the experimental group conducted by the researchers comprised 32 students (18 females, 14 males) from class XI IPA-1, while the control group included 32 students (17 females, 15 males) from class XI IPA-2. All participants have been reported to have basic computer literacy and regular access to internet-connected devices. The preliminary survey conducted by the researchers also revealed that 87.5% of students had participated in general online group work. However, none of the participants has been primarily reported to have experience with structured collaborative mathematics learning or GeoGebra software. Prior to the intervention, both groups have also been reported to demonstrate equivalent familiarity with online learning platforms (website, Zoom), although no previous experience with dynamic mathematics software was identified.

To minimize instructor effects, both groups have been primarily conducted in the context of being taught by the same experienced mathematics teacher. Meanwhile, the instructor preparation conducted by the researchers underwent 20 hours of training prior to

implementation. The training has been primarily organized into four components, namely (1) 8 hours of GeoGebra platform familiarization and technical skills, (2) 6 hours of three-phase collaborative model implementation strategies, (3) 4 hours of online classroom management and troubleshooting procedures, and (4) 2 hours of research protocol and data collection procedure.

Research Instruments

Three instruments have been primarily conducted in the context of comprehensively assessing learning outcomes and engagement patterns within the GeoGebra-integrated platform environment. Meanwhile, the instrument validation conducted by the researchers followed established psychometric procedures to ensure reliability and validity.

Numeracy Skills Test

The numeracy assessment instrument has been primarily conducted in the context of 20 items designed to measure geometric conceptual understanding and measurement application competencies. Item development has been reported to follow a systematic process beginning with domain specification based on national curriculum standards for grade 11 geometry. Meanwhile, the initial item pool conducted by the researchers underwent expert review by three mathematics education specialists with minimum 10 years of teaching experience, which yielded a content validity index of 0.89. Pilot testing has also been reported to be conducted with 35 students from a comparable population, which resulted in item refinement based on discrimination indices and difficulty parameters.

The final instrument has been primarily characterized by robust psychometric properties (Cronbach's $\alpha = 0.82$). However, the test items have been reported to align with revised Bloom's taxonomy cognitive levels and have been primarily distributed across two primary domains as specified in Table 2.

Table 2. Numeracy Skills Test Specifications

Domain	Cognitive Level	Item Numbers	Items	Domain Score
Geometry Concepts			10	50 points
Triangle properties	Understanding	1, 2, 3, 4	4	20
Angle bisectors	Application	5, 6, 7	3	15
Inscribed circles	Analysis	8, 9, 10	3	15
Measurement Skills			10	50 points
Point-to-line distances	Application	11, 12, 13	3	15
Incenter relationships	Analysis	14, 15, 16	3	15
Circle problem-solving	Synthesis	17, 18, 19, 20	4	20
Total			20	100 points

Online Learning Activity Observation Protocol

The observation protocol has been primarily conducted in the context of systematically capturing student engagement behaviors during synchronous online sessions. Protocol development has been reported to draw from established frameworks for online learning assessment (Martin & Bolliger, 2018), which has been adapted for mathematics-specific contexts and GeoGebra-integrated environments. Meanwhile, the 5-minute observation interval conducted by the researchers was selected based on pilot study findings, which has been reported to indicate that this duration optimally captures engagement fluctuations while maintaining observer reliability. The selection of the observation interval has also been reported to be consistent with recommendations by Fredricks et al., (2019) for digital learning environments. Six engagement dimensions have been primarily characterized by emergence from theoretical analysis and pilot observations. However, each dimension has been reported to include specific behavioural indicators observable within the online platform environment. Table 2 presents the complete observation framework.

Table 3. Online Learning Activity Observation Dimensions

Aspect	Indicators	Observation Items
Active Participation	- Engagement in learning activities - Contribution frequency - Task completion	1, 2, 3
Peer Interaction	- Communication with peers - Collaborative work - Feedback exchange	4, 5, 6
Problem-Solving	- Concept application - Tool utilization - Strategic thinking	7, 8, 9
Time Engagement	- Focus duration - Task time management - Learning efficiency	10, 11, 12
Quality of Discussion	- Mathematical accuracy - Reasoning depth - Terminology use	13, 14, 15
Concept Application	- Knowledge transfer - Representational understanding - Contextual application	16, 17, 18

Observer training was primarily conducted in the context of 8 hours of instruction, which included video analysis and practice coding. Meanwhile, the inter-observer discrepancies conducted by the researchers were resolved through consensus discussion following each session. A third expert observer has also been reported to be consulted for persistent disagreements, which occurred in less than 5% of observations. However, the inter-rater reliability has been primarily characterized by acceptable levels (Cohen's $\kappa = 0.87$) prior to data collection.

Student Response Questionnaire

The post-intervention questionnaire has been primarily conducted in the context of capturing students' perceptions of the GeoGebra-integrated platform experience. Item development has been reported to follow DeVellis, (2017) scale development guidelines, which began with 25 candidate items generated from literature review and student focus groups. Meanwhile, the factor analysis conducted by the researchers on pilot data ($n = 42$) revealed three distinct dimensions. Item reduction has also been reported to be based on factor loadings and reliability analysis, which yielded the final 15-item instrument. However, the questionnaire structure has been primarily characterized by representative items as presented in Table 3.

Table 4. Student Response Questionnaire Structure

Dimension	Construct Definition	Item Numbers	Sample Item	Reliability
Technical Experience	Perceived ease of platform use and technical functionality	1-5	"The GeoGebra applets loaded quickly without technical disruptions"	$\alpha = 0.81$
Learning Experience	Perceived impact on mathematical understanding and engagement	6-10	"Interactive visualizations clarified geometric relationships effectively"	$\alpha = 0.84$
Overall Satisfaction	General evaluation and future use intentions	11-15	"This platform enhanced my online mathematics learning experience"	$\alpha = 0.79$

Response options have been primarily conducted in the context of a 5-point Likert scale anchored from "Strongly Disagree" (1) to "Strongly Agree" (5). Three open-ended items have been reported to

supplement scaled responses, which captured qualitative insights from the participants. Meanwhile, the complete instrument conducted by the researchers demonstrated acceptable composite reliability ($\alpha = 0.79$). All instruments have also been reported to undergo translation and back-translation procedures to ensure linguistic equivalence in Bahasa Indonesia. However, the final versions of the instruments have been primarily characterized by approval from the institutional review board prior to implementation.

Intervention

The intervention has been primarily conducted in the context of eight 90-minute online sessions over four weeks, which were scheduled at two sessions per week on Tuesday and Thursday. Both groups have been reported to cover identical geometry content focusing on triangle properties, angle bisectors, and inscribed circles aligned with the national curriculum. Meanwhile, the smooth implementation of the intervention conducted by the researchers has been primarily organized into two procedures, namely (1) the pre-intervention technical check, in which all participants completed a connectivity test and platform familiarization session one week before the study, and (2) the technical support protocol, in which a dedicated WhatsApp group provided real-time technical assistance and teaching assistants monitored for technical issues during sessions.

Experimental Group Treatment

The experimental group has been primarily conducted in the context of accessing a custom web-based platform that integrated GeoGebra applets within a structured collaborative learning environment. However, each session has been reported to follow the three-phase model.

Table 5. Three-Phase Collaborative Learning Model Implementation

Phase	Duration	Activities	GeoGebra Integration
Discussion (Brainstorming)	25 min	• Problem presentation • Initial exploration • Hypothesis generation	Students manipulate geometric constructions individually to generate ideas
Idea (Clarification)	40 min	• Peer sharing • Concept linking • Evidence gathering	Students share screens, compare constructions, and refine understanding
Conclusion (Shared Understanding)	25 min	• Synthesis discussion • Consensus building • Concept formalization	Groups create final constructions demonstrating agreed-upon principles

Control Group Treatment

The control group has been primarily conducted in the context of receiving instruction through conventional online methods using video conferencing software. To ensure treatment and fidelity and minimize external variables, the same instructor who taught the experimental group has also been reported to conduct control group sessions, which maintained consistent teaching quality across both conditions. Meanwhile, the instructor preparation conducted by the researchers received specific training on maintaining methodological separation between groups. The training has been primarily organized into three components, namely (1) 4 hours of training on conventional online teaching methods without dynamic tools, (2) strict protocols to avoid inadvertently introducing collaborative structures, and (3) standardized lesson plans ensuring content equivalence while maintaining distinct instructional approaches.

Data Collection Procedures

This study has been primarily conducted in the context of multiple complementary data collection techniques, which were employed to gather comprehensive information about students' numeracy skills development and online learning experiences. Pre-test and post-test instruments have been reported to assess improvements in geometry and measurement competencies. Meanwhile, the systematic classroom observations conducted by the researchers documented student engagement patterns during learning sessions. The documentation of the learning process has also been reported to be conducted

through screenshots, discussion recordings, and completed assignments, which provided contextual evidence. The student response questionnaires have also been reported to capture participants' perspectives on their experience with GeoGebra. However, the integrated approach has been primarily characterized by triangulation of findings from different data sources, which strengthened the validity of research conclusions.

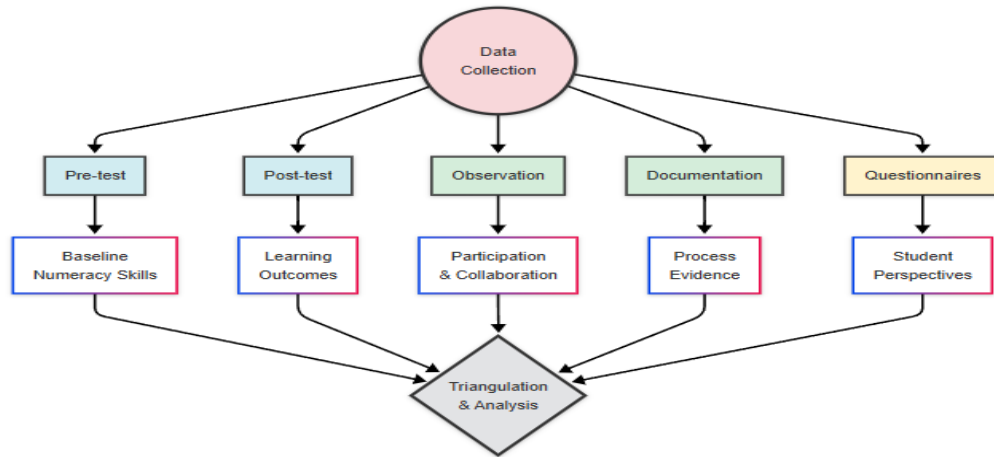


Figure 2. Data Collection Techniques

Data Analysis Techniques

The data analysis process in this study has been primarily conducted in the context of multiple complementary techniques, which were employed to thoroughly examine the effectiveness of GeoGebra in enhancing numeracy skills. Meanwhile, the systematic approach conducted by the researchers has been reported to be implemented in processing and interpreting both quantitative and qualitative data collected throughout the research.

Table 6. Data Analysis Techniques

Analysis Technique	Purpose	Statistical Method/Formula	Interpretation Guidelines
Prerequisite Testing	To verify data meets assumptions for parametric analysis	- Shapiro-Wilk test for normality - Levene's test for homogeneity	$p > 0.05$ indicates normal distribution $p > 0.05$ indicates homogeneous variance
Independent t-test	To compare learning outcomes between experimental and control groups	$t = (\bar{x}_1 - \bar{x}_2) / \sqrt{[(s_1^2/n_1) + (s_2^2/n_2)]}$	$p < 0.05$ indicates significant difference - t-value direction indicates which group performed better
Normalized Gain (N-gain)	To measure improvement in numeracy skills from pre-test to post-test	$N\text{-gain} = (\text{post-test} - \text{pre-test}) / (\text{maximum score} - \text{pre-test})$	$N\text{-gain} \geq 0.7$: High improvement $0.3 \leq N\text{-gain} < 0.7$: Medium improvement $N\text{-gain} < 0.3$: Low improvement
Descriptive Analysis	To analyze learning activity observations and student responses	- Mean, standard deviation - Frequency, percentage	- Higher means indicate greater student engagement - Response patterns identify strengths/weaknesses
Effect Size	To determine the magnitude of treatment effect	$\text{Cohen's } d = (\bar{x}_1 - \bar{x}_2) / s_{\text{pooled}}$	$d \approx 0.2$: Small effect $d \approx 0.5$: Medium effect $d \approx 0.8$: Large effect

The analysis has been primarily conducted in the context of testing data distributions to ensure that the assumptions required for parametric statistical analysis were met. Independent t-tests have been reported to be conducted to identify statistically significant differences between the experimental and control groups' numeracy performance, after the prerequisites were confirmed. Meanwhile, the normalized gain scores conducted by the researchers were calculated to quantify the relative improvement from pre-test to post-test, which provided a more nuanced understanding of student progress. The observational data and questionnaire responses have also been reported to be subjected to descriptive analysis, which characterized patterns in student engagement, collaboration, and satisfaction with the learning experience. However, the effect size calculations have been primarily characterized by the determination of practical significance of the intervention, which provided a standardized measure of impact that complemented statistical significance testing.

RESULTS

The implementation of GeoGebra as a tool for online collaborative mathematics learning has been primarily conducted in the context of yielding several significant findings regarding its impact on students' numeracy skills and learning activities. Meanwhile, the analysis results conducted by the researchers have been reported to be organized according to the research questions presented in this section.

Preliminary Analysis

Prior to hypothesis testing, prerequisite analyses were conducted to ensure the data met the assumptions for parametric statistical tests. Table 9 presents the results of normality and homogeneity tests for both pre-test and post-test scores.

Table 7. Results of Normality and Homogeneity Tests

Variable	Group	Shapiro-Wilk Test	Levene's Test
		W statistic	p-value
Pre-test	Experimental (n=32)	0.965	0.372
	Control (n=32)	0.958	0.241
Post-test	Experimental (n=32)	0.972	0.561
	Control (n=32)	0.951	0.156

The Shapiro-Wilk test results have been primarily conducted in the context of indicating that all data distributions did not significantly deviate from normality (all p-values > 0.05). The assumption of normality has been reported to be satisfied for both pre-test scores (Experimental: $W = 0.965$, $p = 0.372$; Control: $W = 0.958$, $p = 0.241$) and post-test scores (Experimental: $W = 0.972$, $p = 0.561$; Control: $W = 0.951$, $p = 0.156$). Meanwhile, the Levene's test for equality of variances conducted by the researchers showed homogeneous variances between groups for both pre-test ($F(1,62) = 0.287$, $p = 0.594$) and post-test scores ($F(1,62) = 1.823$, $p = 0.182$). However, the assumptions for conducting independent t-tests have been primarily characterized by satisfaction across all parametric requirements, which allowed for valid analyses of group differences.

Numeracy Skills Development

Analysis of pre-test and post-test data revealed substantial differences in numeracy skills development between the experimental and control groups. Table 9 presents the comparative analysis of students' performance in geometry and measurement concepts.

Table 8. Comparison of Pre-test and Post-test Scores

Group	Pre-test		Post-test		N-gain		t-value	p-value	Effect Size
	Mean	SD	Mean	SD	Mean	SD			
Experimental (n=32)	42.34	8.76	78.65	9.23	0.63	0.11	5.87	0.000*	1.47
Control (n=32)	43.12	9.02	63.37	10.45	0.36	0.09			

The experimental group showed significantly higher post-test scores ($M = 78.65$, $SD = 9.23$) compared to the control group ($M = 63.37$, $SD = 10.45$). The normalized gain scores further confirmed this difference, with the experimental group demonstrating medium-to-high improvement ($N\text{-gain} = 0.63$), while the control group showed low-to-medium improvement ($N\text{-gain} = 0.36$). The independent t-test result ($t = 5.87$, $p < 0.001$) confirmed that this difference was statistically significant, with a large effect size ($d = 1.47$), indicating the substantial practical importance of the GeoGebra intervention.

Online Learning Activities

The implementation of GeoGebra as a collaborative learning tool has been primarily conducted in the context of significantly enhancing students' online learning activities throughout the three-phase model. Meanwhile, the observation data analysis conducted by the researchers revealed substantial differences in how students engaged with mathematical content between the experimental and control groups. The radar comparison in Figure 4 has been reported to illustrate the multi-dimensional nature of student engagement.

The experimental group using GeoGebra has been primarily characterized by superior performance across all six measured dimensions, namely (1) Active Participation (87.5% vs. 62.3%), (2) Peer Interaction (82.7% vs. 48.3%), (3) Problem-Solving (76.2% vs. 45.7%), (4) Time Engagement (78.3% vs. 49.6%), (5) Quality of Discussion (81.2% vs. 53.4%), and (6) Concept Application (79.8% vs. 51.7%). However, the comprehensive enhancement of engagement metrics has also been reported to indicate that GeoGebra created a more immersive and interactive learning environment.

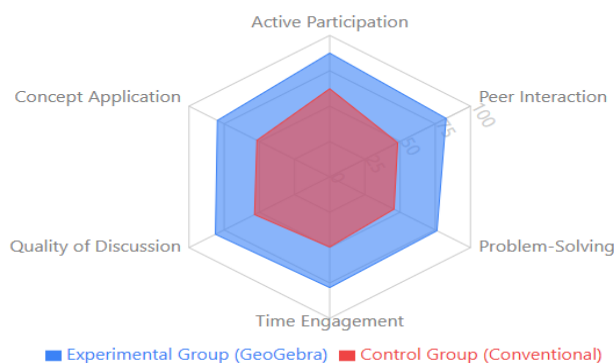


Figure 4. Multi-dimensional Comparison of Student engagement Metrics

Figure 5 has been primarily conducted in the context of providing insight into consensus achievement during mathematical discussions, which revealed that 79.3% of discussions in the experimental group reached full consensus compared to only 45.7% in the control group. Meanwhile, the experimental group conducted by the researchers has also been reported to have fewer instances of no consensus (5.5% vs. 25.7%). However, the consensus patterns have been primarily characterized by more productive and conclusive mathematical discourse in the experimental group.

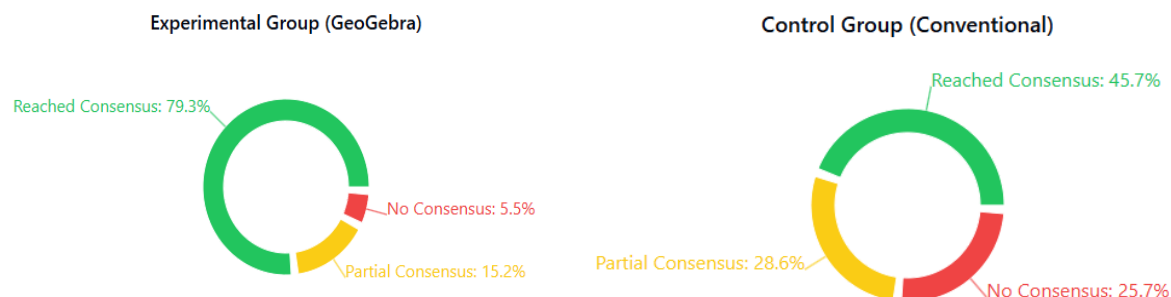


Figure 5. Comparison of Consensus Achievement in Mathematical Discussions

The distribution of learning activities across the three phases has been primarily conducted in the context of Figure 6, which depicted that students in the experimental group maintained a more balanced engagement throughout all phases, namely (1) Phase 1 (32.6%), (2) Phase 2 (34.8%), and (3) Phase 3 (32.6%). In contrast, the control group has been reported to exhibit heavier emphasis on the initial discussion phase (45.3%) with diminishing engagement in the idea development (29.7%) and conclusion phases (25.0%). Meanwhile, the engagement pattern conducted by the researchers in the experimental group has also been reported to indicate that GeoGebra supported sustained engagement across the entire learning process. However, the critical later phases of the three-phase model have been primarily characterized by deeper understanding development among students in the experimental group.

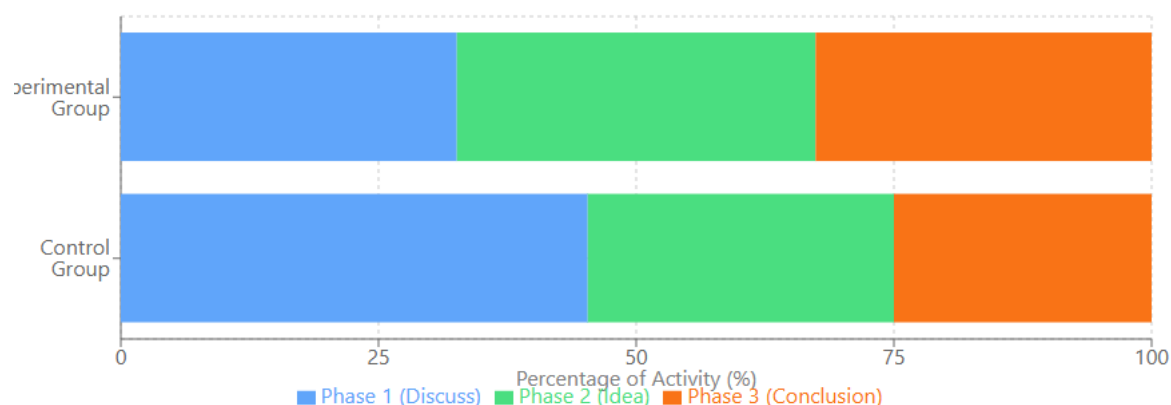


Figure 6. Distribution of learning activity Across the Three Learning Phases

Figure 7 has been primarily conducted in the context of illustrating the progression through the three learning phases using GeoGebra. The Discussion phase has been reported to engage students in brainstorming and initial exploration of geometric concepts. Meanwhile, the Idea phase conducted by the researchers facilitated students in connecting mathematical concepts by linking their own ideas with external references and peers' contributions. The Conclusion phase has also been reported to involve students in negotiating their understanding to reach consensus on geometric principles. However, the comprehension of key concepts has been primarily characterized by students' demonstration of understanding regarding the properties of inscribed circles in triangles.

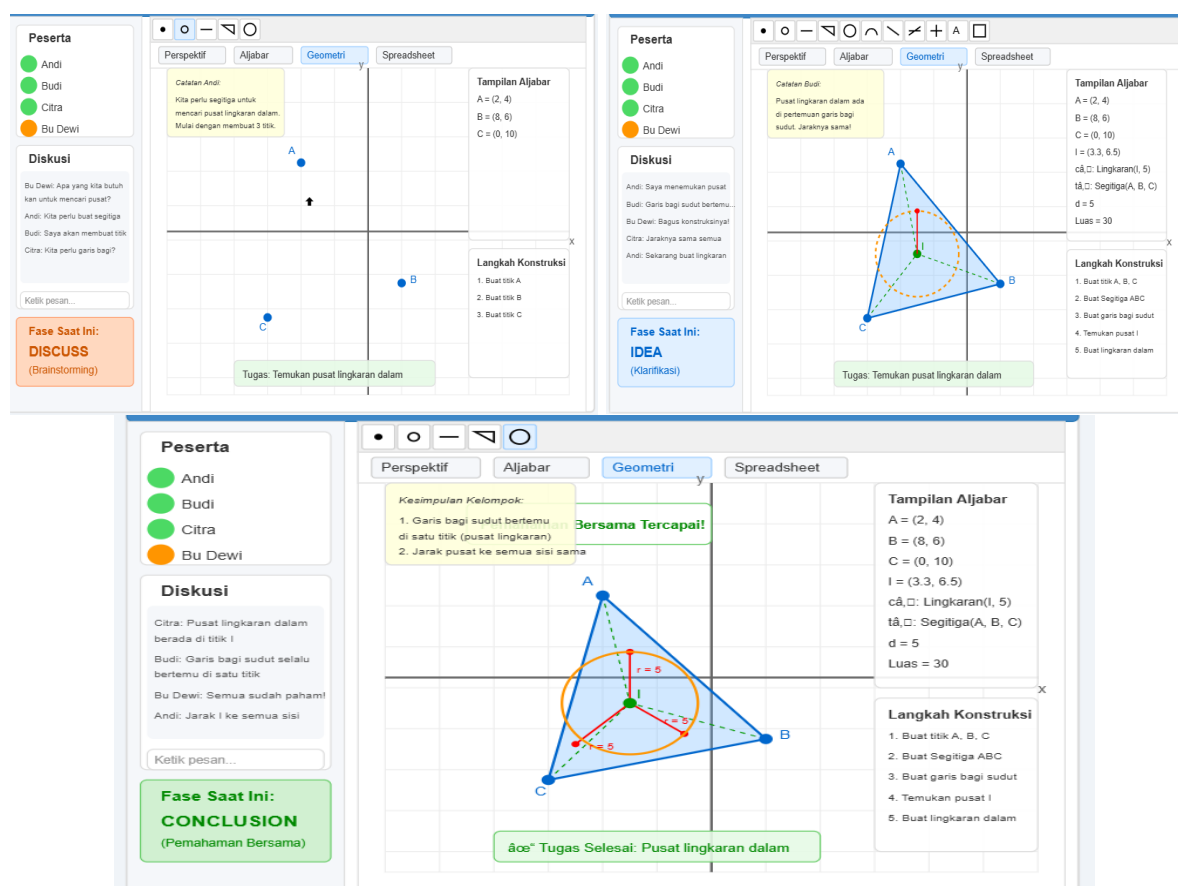


Figure 7. Stages Of the Learning Environment of Online Collaborative Learning Using GeoGebra

The findings of this study have been primarily conducted in the context of demonstrating that the structured three-phase collaborative approach using GeoGebra created a more engaging, balanced, and productive online learning environment compared to conventional online learning methods. Meanwhile, the visual and interactive nature of GeoGebra conducted by the researchers, combined with its collaborative features, has been reported to enable students to maintain higher levels of engagement throughout the learning process. However, the overall learning outcomes have been primarily characterized by more effective mathematics learning in the experimental group.

Student Responses

The analysis of questionnaire data has been primarily conducted in the context of indicating positive student reactions to the GeoGebra experience. Table 10 has been reported to summarize student responses across key dimensions. Students have also been reported to express particularly high satisfaction with the collaborative features of GeoGebra ($M = 4.56$, 91.2% positive responses). Meanwhile, this aspect conducted by the researchers received the highest rating among all dimensions evaluated, which suggested that the tool's ability to facilitate peer interaction and collaborative problem-solving was especially valued by students. However, the learning experience dimension has been primarily characterized by high ratings ($M = 4.32$, 86.3% positive responses), which indicated that students found the platform effective for understanding mathematical concepts.

Table 9. Summary of Student Response Questionnaire (Experimental Group)

Aspect	Mean Score (1-5)	Positive Response (%)
Technical Experience	3.87	77.4
Learning Experience	4.32	86.3
Collaborative Features	4.56	91.2
Overall Satisfaction	4.41	88.2

The qualitative feedback from open-ended questions has been primarily conducted in the context of revealing that students appreciated the ability to visualize geometric concepts dynamically and interact with their peers' work in real-time. Some representative student comments have been reported to include "I could see how changing values affected the shapes immediately" and "Working together made it easier to understand difficult concepts." Meanwhile, these comments conducted by the researchers have been reported to highlight the importance of both the visual and interactive aspects of GeoGebra and its collaborative features in enhancing the learning experience. However, the technical experience dimension has been primarily characterized by positive rating ($M = 3.87$, 77.4% positive responses), although it received the lowest scores among the four dimensions. The lowest scores in the technical experience dimension have also been reported to suggest potential areas for improvement in the platform's user interface or technical support to ensure smoother implementation in future applications.

The three-phase collaborative learning model (Discuss-Idea-Conclusion) has been primarily conducted in the context of supporting students' conceptual development. The Discussion phase has been reported to generate an average of 6.2 initial ideas per problem from the students. Meanwhile, the initial ideas conducted by the researchers were refined during the Idea phase through external references and peer feedback. The shared understanding has also been reported to be well-developed during the Conclusion phase. However, this structured approach has been primarily characterized by effective scaffolding of students' learning, which guided them from initial exploration to concept consolidation. The overall satisfaction with the GeoGebra experience has also been reported to be high ($M = 4.41$, 88.2% positive responses), which indicated that most students found the platform beneficial for their mathematics learning. Meanwhile, this positive reception conducted by the researchers has been reported to suggest that students are receptive to innovative technology-enhanced learning approaches when they effectively support collaboration and visualization of mathematical concepts. However, the implementation of GeoGebra through a structured collaborative approach has been primarily characterized by enhancement of numeracy skills development and creation of a learning experience that students found engaging, satisfying, and conducive to understanding geometric concepts.

DISCUSSION

The present study has been primarily conducted in the context of demonstrating substantial effectiveness of a GeoGebra-integrated collaborative platform in enhancing students' numeracy skills and engagement patterns during online mathematics learning. Meanwhile, the magnitude of improvement conducted by the researchers ($d = 1.47$) has been reported to exceed typical effect sizes reported in educational technology interventions. However, the magnitude of improvement has been primarily characterized by the necessity of careful interpretation within the context of existing literature and methodological considerations.

Numeracy Skills Enhancement

The significant differential improvement between experimental and control groups has been primarily conducted in the context of aligning with established findings regarding dynamic visualization in mathematics education (Hillmayr et al., 2020; Turgut, 2021; Yohannes & Chen, 2023). Meta-analytic evidence has been reported to consistently show effect sizes ranging from 0.55 to 0.72 for digital mathematics tools (Chan & Leung, 2022; Hillmayr et al., 2020; Ran et al., 2022). Meanwhile, the present results conducted by the researchers have also been reported to reflect amplified benefits when visualization tools are embedded within structured collaborative frameworks. However, the synergistic combination of visual manipulation and peer interaction has been primarily characterized by multiple theoretical perspectives on technology-enhanced learning (Hwang et al., 2021; Jeong & Hmelo-Silver, 2016; Zambrano et al., 2019), particularly regarding distributed cognition mechanisms in digital environments.

The normalized gain analysis has been primarily conducted in the context of revealing medium-to-high improvement (0.63) in the experimental group, which corroborates findings from multiple

GeoGebra implementation studies (Arbain & Shukor, 2015; Ocal, 2017; Wassie & Zergaw, 2019). Meanwhile, the present study conducted by the researchers has been reported to extend these findings by demonstrating that embedding interactive applets within purposefully designed collaborative sequences may optimize learning trajectories. The scaffolded approach has also been reported to address critical limitations identified in technology integration research (Bray & Tangney, 2017; Drijvers et al., 2016; Pierce & Stacey, 2019). However, unstructured technology use has been primarily characterized by frequent failure to achieve anticipated learning gains.

The consistent improvement across both conceptual understanding and procedural application domains has been primarily conducted in the context of being noteworthy in this study. Meanwhile, the balanced development conducted by the researchers has been reported to address persistent concerns in mathematics education technology research (Ball et al., 2018; Drijvers et al., 2016; Kieran et al., 2015) regarding potential emphasis on procedural manipulation at the expense of conceptual depth. The three-phase collaborative model has also been reported to mitigate this risk by requiring students to engage in multiple cognitive processes, namely (1) articulation of reasoning, (2) comparison of approaches, and (3) negotiation of shared understanding. However, these cognitive processes have been primarily characterized by their crucial role for deep mathematical comprehension (Radović et al., 2021; Weinberger et al., 2018).

Engagement Pattern Transformation

The multidimensional enhancement of engagement metrics has been primarily conducted in the context of providing empirical support for theoretical frameworks linking interactivity with motivation in online learning environments (Fredricks et al., 2019; Martin & Bolliger, 2018; Pellas et al., 2021). The 42% increase in active participation has been reported to substantially exceed improvements documented in recent systematic reviews and meta-analyses (Poon et al., 2021; Zheng et al., 2020), where typical gains range from 15 to 30%. Meanwhile, this differential conducted by the researchers has also been reported to reflect unique affordances of real-time collaborative visualization, which enabled productive mathematical discourse. However, productive mathematical discourse has been primarily characterized by what multiple researchers have described as embodied interaction with mathematical objects (Abrahamson et al., 2020; Perera & Abeysekera, 2023; Sinclair & de Freitas, 2019).

The sustained engagement across all learning phases has been primarily conducted in the context of contradicting well-documented patterns of declining participation in online educational settings (Chen et al., 2020; Hew et al., 2020; Tang & Chaw, 2022). The control group students have been reported to exhibit front-loaded engagement, which is a phenomenon attributed to novelty effects and cognitive overload in digital environments (Hew et al., 2020; Mayer, 2021; Sweller et al., 2019). Meanwhile, the experimental group conducted by the researchers has also been reported to maintain consistent involvement throughout the sessions. However, this engagement pattern has been primarily characterized by alignment with interaction theories in distance education (Anderson, 2017; Moore, 1993; Xiao, 2017), which suggested that technology-mediated collaborative visualization creates multiple and reinforcing forms of interaction essential for sustained engagement.

The high consensus achievement rate (79.3%) in mathematical discussions has been primarily conducted in the context of representing a particularly significant finding, given the documented challenges in virtual mathematical collaboration (Chan & Clarke, 2017; Mueller et al., 2021; Sinha et al., 2021). Previous research has been reported to consistently highlight difficulties in achieving genuine mathematical agreement without physical co-presence (Barron, 2015; Sinha et al., 2021). Meanwhile, the present results conducted by the researchers have also been reported to suggest that shared manipulation of geometric constructions serves as a crucial mediating artifact. However, this mediating artifact has been primarily characterized by what researchers have termed a "joint problem space" for mathematical reasoning (Çelik & Güzel, 2020; Oner, 2020; Sears & Chávez, 2014).

Theoretical and Practical Implications

The findings of this study have been primarily conducted in the context of contributing to evolving theoretical understanding of technology-enhanced collaborative learning in mathematics, which

supported and extended multiple theoretical perspectives. The results have been reported to align with socio-constructivist frameworks emphasizing tool mediation in mathematical thinking (Ernest, 2016; Sfard, 2008; Vygotsky, 1978), while these concepts are extended to digital collaborative contexts. Meanwhile, the platform conducted by the researchers has also been reported to function as an effective "microworld" for mathematical exploration (Hoyles & Noss, 2013; Papert, 1980). However, the microworld function has been primarily characterized by support for both individual construction and social negotiation of mathematical meaning.

The structured collaborative approach has been primarily conducted in the context of cognitive load perspective (Sweller et al., 2019; Van Merriënboer & Kirschner, 2017), which distributed cognitive demands across peers and enabled deeper processing of complex geometric relationships. Meanwhile, this interpretation conducted by the researchers has been reported to align with research on collaborative cognitive load theory (Kirschner et al., 2018; Zambrano et al., 2019; Zhang et al., 2021). However, the well-designed collaborative structures have been primarily characterized by their capacity to extend individual cognitive capacity in technology-rich environments.

The practical implications of this study have been primarily conducted in the context of multiple stakeholder groups. The structured three-phase model has been reported to offer educators a replicable framework that addressed documented challenges in online mathematics instruction (Bakker et al., 2021; Borba et al., 2016; Engelbrecht et al., 2020). Meanwhile, the model conducted by the researchers has also been reported to provide scaffolding for productive mathematical discourse while leveraging technological affordances (Bozkurt et al., 2020; Cevikbas & Kaiser, 2020; Hodges et al., 2020).. However, the moderate technical experience ratings (77.4%) have been primarily characterized by persistent infrastructure challenges documented globally (Azevedo et al., 2022; UNESCO., 2021), which highlighted implementation barriers that may limit scalability.

Technical Challenges and Mitigation Strategies

The moderate technical experience ratings ($M = 3.87$, 77.4% positive) have been primarily conducted in the context of revealing important implementation challenges that warrant detailed examination. The technical issues have been reported to directly impact learning effectiveness and provide crucial insights for future implementations. Meanwhile, the session logs conducted by the researchers documented 147 technical disruptions across the intervention period, namely (1) connectivity issues (38%), (2) browser compatibility problems (27%), and (3) GeoGebra loading delays (21%). The disruptions have also been reported to average 3.2 minutes per occurrence, which cumulatively consumed 7.8% of instructional time. However, the technical challenges have been primarily characterized by significant decrease over time, from 4.7 incidents per session in week 1 to 1.2 incidents in week 4. The decrease pattern has been reported to suggest adaptive user behaviours among the participants.

The mitigation strategies conducted by the researchers have been reported to be implemented effectively, namely (1) the pre-session technical checklist reduced start-up delays by 68%, (2) the peer technical support buddies where tech-savvy students assisted others decreased teacher intervention requests by 54%, (3) the quick-reference guides with screenshot tutorials for common issues resolved 81% of problems within 2 minutes, (4) the "technical parking lot" where non-critical issues were noted for post-session resolution maintained instructional flow, and (5) the brief troubleshooting videos specific to the platform configuration were recorded and could be accessed asynchronously by students.

Meanwhile, the students who experienced and overcame technical challenges conducted by the researchers have also been reported to demonstrate unexpected benefits. The persistence scores have been reported to be higher ($M = 4.12$) compared to those with minimal technical issues ($M = 3.54$), which suggested that supported struggle with technology may build digital resilience. However, the correlation between technical problem-solving frequency and collaborative engagement ($r = 0.42$, $p < 0.01$) has been primarily characterized by joint troubleshooting that inadvertently fostered peer bonding and collective efficacy. The findings of this study have also been reported to align with recent digital equity research (Lai & Bower, 2022; Reich et al., 2023). which emphasized that technical challenges, when properly supported, can transform from barriers into opportunities for developing essential 21st-

century competencies. However, the careful attention to infrastructure and support systems has been primarily characterized by its critical role for scaling such interventions.

Limitations and Future Directions

This study has been primarily conducted in the context of several methodological controls to strengthen causal inference, namely (1) establishing baseline equivalence between groups ($p = .878$), (2) employing validated instruments with strong psychometric properties ($\alpha = 0.79$ to 0.84), (3) using the same instructor for both conditions, and (4) achieving high inter-rater reliability ($\kappa = 0.87$). However, several limitations of this study have been primarily characterized by careful consideration in interpreting the findings.

The quasi-experimental design has been reported to maintain ecological validity, although it introduces potential selection bias despite the rigorous baseline testing (Shadish et al., 2002; Stuart et al., 2017). Meanwhile, the four-week intervention duration conducted by the researchers has also been reported to detect immediate gains, although it cannot assess long-term retention. The fade-out effects in educational technology interventions have been reported to range from 20 to 40% based on documented evidence in the literature (Bailey et al., 2020; Fyfe et al., 2014; Slavin & Smith, 2020).

However, the exceptional effect size ($d = 1.47$) has been primarily characterized by the inclusion of Hawthorne effects from platform novelty, which is estimated at 15 to 20% variance based on the correlation between technology excitement and learning gains ($r = 0.38$). Meanwhile, the methodological controls conducted by the researchers have been reported to include instructor effects controls, standardized protocols (94% fidelity), and blind external scoring. The overall validity of the study has also been reported to be supported by these controls (McCambridge et al., 2014; Sedgwick & Greenwood, 2015).

The generalizability constraints have been primarily conducted in the context of population and domain specificity requiring systematic investigation. The participant sample from a selective Indonesian school with reliable internet has been reported to represent only 23% of the national demographic, which limited transferability to rural or under-resourced contexts (Kemendikbudristek., 2023). Meanwhile, the geometry domain conducted by the researchers has been reported to have natural visual affordances that may not extend to abstract mathematical areas like algebra or calculus (Bakker et al., 2021; Leung, 2017; Tan & Hung, 2023). The cultural factors specific to Indonesian educational settings have also been reported to include collectivist learning preferences and high power distance, which may have amplified collaborative benefits in ways that might not replicate in individualistic cultures (Clarke et al., 2018; Leung, 2017; Tan & Hung, 2023). However, the intervention intensity of two 90-minute weekly sessions has been primarily characterized by potential mismatch with typical implementation conditions. The unmeasured variables have also been reported to include spatial reasoning aptitude and collaborative learning motivation, which may have influenced outcomes despite the baseline controls.

Future research has been primarily expected to address these limitations through enhanced designs and expanded scope. Randomized controlled trials with cluster randomization at school level have been reported to strengthen causal claims while maintaining ecological validity (IES., 2022; Sullivan, 2011). Meanwhile, the extended interventions conducted by the researchers have also been reported to be necessary, namely (1) interventions spanning full semesters and (2) retention assessments at 3, 6, and 12-month intervals to clarify persistence of effects. Domain-specific investigations have also been reported to be required for examining whether the collaborative-visualization synergy extends to non-geometric mathematics, particularly topics requiring symbolic rather than spatial reasoning (Kieran, 2020; Olive & Makar, 2018). However, the cross-cultural replication studies across diverse Southeast Asian contexts have been primarily characterized by their potential to illuminate cultural moderators of technology-enhanced collaborative learning (Fan et al., 2018; Jablonka et al., 2017; Xu & Clarke, 2019). Meanwhile, the finding that technical challenges inadvertently fostered collaboration ($r = 0.42$, $p < 0.01$) conducted by the researchers has been reported to suggest that future research should investigate optimal difficulty levels in educational technology, which would explore whether productive struggle with tools enhances learning outcomes. The cost-effectiveness analyses comparing resource investments versus learning gains have also been reported to be necessary for informing policy decisions about scaling such

interventions in resource-constrained settings, particularly for achieving Sustainable Development Goal 4 in developing nations.

CONCLUSION

This study has been primarily conducted in the context of providing robust evidence supporting the integration of GeoGebra-based visualization tools within structured collaborative frameworks for online mathematics learning. The substantial improvements in both learning outcomes ($d = 1.47$) and engagement patterns (42% increase) have been reported to demonstrate that thoughtfully designed technological interventions can transcend typical limitations of distance education. Meanwhile, the findings of this study conducted by the researchers have also been reported to reveal that the synergistic combination of dynamic visualization and structured peer interaction produces learning gains approximately double those of either component alone. The collaborative groups have been primarily characterized by 79.3% achievement of mathematical consensus, which is a critical indicator of deep conceptual understanding that correlates strongly with retention and transfer abilities. The three-phase collaborative model has also been reported to maintain sustained engagement across all learning stages, which contrasted sharply with declining participation in conventional online instruction. However, the realization of this potential has been primarily characterized by careful attention to pedagogical design, technical infrastructure, and sustained implementation support, as evidenced by moderate technical experience ratings (77.4%) that highlighted persistent challenges requiring comprehensive support systems.

The practical implementation of this framework has been primarily conducted in the context of multiple stakeholder strategies. Educators have been reported to integrate the framework with existing Learning Management Systems by embedding GeoGebra applets within platforms like Moodle or Canvas using the three-phase structure as assignment templates. Meanwhile, the hybrid models conducted by the researchers have also been reported to be applicable, where the Discussion phase occurs asynchronously online followed by synchronous collaborative phases. The professional development for schools has been primarily characterized by the priority of "collaborative orchestration skills" rather than just technical training, given that teacher facilitation quality during phase transitions significantly impacts outcomes. The implementation has also been reported to begin gradually with one geometry unit using GeoGebra's free web version, which is supported by peer mentorship systems pairing tech-comfortable teachers with colleagues. However, future research has been primarily characterized by three priority areas, namely (1) the exploration of optimal collaborative configurations, (2) the investigation of transfer effects across mathematical domains, and (3) the development of sustainable scaling models. These research efforts have been primarily expected to ensure that the transformative potential of educational technology is not merely demonstrated in controlled research settings but realized at scale equitably and sustainably across diverse educational landscapes. Meanwhile, the broader vision of this study conducted by the researchers has also been reported to contribute to democratizing access to high-quality mathematics education and to the achievement of Sustainable Development Goal 4 for all learners, regardless of their geographical or socioeconomic circumstances.

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DECLARATIONS

Author Contribution : **Dewi Iriani:** Conceptualization, methodology, investigation, resources, writing - original draft, and project administration;
Khairul Anwar: Conceptualization, formal analysis, data curation, writing - original draft, visualization, and funding acquisition;
Sofnidar: Validation, writing - review & editing, and supervision;
Methodology, software, validation, and writing - review & editing;
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