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Oluwanife Segun Falebita¹, Joseph Oluwatosin
Fadipe²

¹Mathematics, Science and Technology Education
Department, University of Zululand, KwaDlangezwa,
KwaZulu-Natal, South Africa, FalebitaO@unizulu.ac.za

²Science Education Department, Federal University Oye-
Ekiti, Nigeria

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Transforming circle geometry learning with geogebra as a digital learning environment: Students' performance and self-efficacy

Oluwanife Segun Falebita^{1*}, Joseph Oluwatosin Fadipe²

¹Mathematics, Science and Technology Education Department, University of Zululand, KwaDlangezwa, KwaZulu-Natal, South Africa, oluwanifefalebita@gmail.com

²Science Education Department, Federal University Oye-Ekiti, Ekiti, Nigeria, toscojosh@gmail.com

Corresponding Email: oluwanifefalebita@gmail.com

Abstract

Dynamic geometry environments may support mathematics achievement, but their relationships with geometry self-efficacy and gender remain insufficiently understood. This quasi-experimental study examined GeoGebra-supported circle geometry instruction among 76 senior secondary students in Ekiti State, Nigeria. A nonequivalent pretest-posttest control group design compared one intact GeoGebra class ($n = 36$) with a conventional instruction class ($n = 40$) over six weeks. Instruments comprised a 20-item Circle Geometry Performance Test ($KR-20 = .78$) and a 10-item Geometry Self-Efficacy Scale ($\alpha = .81$). Two-way ANCOVA controlled for corresponding pretest scores. Instructional group was significantly associated with posttest performance, $F(1, 71) = 24.41$, $p < .001$, partial $\eta^2 = .256$, and self-efficacy, $F(1, 71) = 11.92$, $p = .001$, partial $\eta^2 = .144$, favoring GeoGebra-supported instruction. No instructional strategy $\times$ gender interaction was detected for either outcome, although the sample limited sensitivity to moderation. Because each condition involved one class from a different school, instructional differences were confounded with school and teacher characteristics, precluding causal conclusions. The findings suggest that guided GeoGebra exploration may support circle geometry learning and perceived capability. Its potential application in blended and remote environments requires further investigation, alongside replication across multiple schools and classes and verification of model assumptions.

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1. Introduction

Geometry occupies a central place in school mathematics because it requires students to coordinate visual representations, spatial relationships, and deductive reasoning rather than to rely on computational procedures alone. Within geometry, circle geometry is particularly demanding. Students must recognize relationships among angles, arcs, chords, tangents, and cyclic quadrilaterals, often in unfamiliar configurations, and they must understand why these relationships remain invariant when a figure

changes. When instruction relies on static textbook diagrams, students frequently memorize circle theorems without understanding them and then struggle to apply them to new problems (Akpage et al., [2026](#); Fujita et al., [2020](#)). Difficulties in interpreting geometric relationships and applying formal properties to problem solving remain widely reported in secondary education, including in Nigeria (Dahal et al., [2022](#); Hassan et al., [2023](#); Taufan et al., [2024](#)).

Dynamic geometry environments offer a direct response to this problem. GeoGebra, a freely available dynamic mathematics software package, allows learners to construct geometric objects, drag their components, and observe in real time which properties change and which remain constant. These affordances support mathematical visualization and help students connect representations with reasoning (Greefrath et al., [2018](#); Sugiarni et al., [2025](#); Suparman et al., [2024](#); Ziatdinov & Valles, [2022](#)). In circle geometry, for example, a student can drag a point along a circle and observe that the inscribed angle subtending a fixed arc remains unchanged, thereby turning an abstract theorem into an observable invariant that can be conjectured, tested, and explained. Not surprisingly, research on GeoGebra has expanded rapidly, and geometry remains its most frequent area of application (Gökçe & Güner, [2022](#); Yohannes & Chen, [2023](#)).

The evidence on learning outcomes is encouraging but not uniform. Meta-analyses report a moderate positive effect of dynamic mathematics software on students' performance, and they show that this effect varies with intervention duration, mode of use, and cultural context (Hillmayr et al., [2020](#); Ji et al., [2024](#); Juandi et al., [2021](#)). Individual studies have associated GeoGebra-supported instruction with higher achievement in secondary mathematics (Mosese & Ogbonnaya, [2021](#); Mthethwa et al., [2020](#); Zulnaidi et al., [2020](#)), including circle geometry and circle theorems (Akpage et al., [2026](#); Mollakuqe et al., [2021](#)), as well as with more positive attitudes and stronger motivation (Birgin & Topuz, [2021](#); Kassa et al., [2025](#); Romero & García, [2024](#)). At the same time, the benefits depend on how teachers integrate the software into instruction and on the conditions of the school, including the availability of devices in resource-constrained classrooms (Batiibwe, [2024](#); Fung et al., [2024](#); Manganyana et al., [2020](#)). The pedagogical use of GeoGebra, rather than its mere availability, therefore determines its value.

Achievement, however, captures only part of what students take away from geometry instruction. Students' beliefs about their capability to perform mathematical tasks, that is, their self-efficacy, shape how they approach challenging problems and how long they persist when difficulties arise. Longitudinal evidence shows that mathematics self-efficacy and achievement are reciprocally related, so that gains in one tend to support gains in the other (Arens et al., [2022](#)). Evidence on whether technology-enhanced instruction strengthens self-efficacy is nevertheless limited and mixed. GeoGebra-based teaching has been associated with higher self-efficacy and self-regulation (Zetriuslita et al., [2021](#)), and integrating GeoGebra into flipped online learning has been linked to stronger self-regulated learning (Ishartono et al., [2022](#)). In contrast, a mobile mathematics application used in remote and hybrid settings improved achievement and reduced anxiety but left self-efficacy largely unchanged (Mamolo & Sugano, [2024](#)).

Moreover, most technology studies have prioritized cognitive outcomes such as achievement or mathematical communication (Kusumah et al., [2020](#); Zulnaldi et al., [2020](#)), and we are not aware of studies that have examined geometry self-efficacy as an outcome of GeoGebra-supported circle geometry instruction.

Social cognitive theory provides a coherent rationale for expecting GeoGebra-supported instruction to influence both performance and self-efficacy. The theory posits reciprocal relationships among personal factors, behavior, and the learning environment, and it identifies self-efficacy as a key personal factor shaped by the experiences that the environment affords (Bandura, [1986](#); Schunk & DiBenedetto, [2020](#)). Digital learning environments can also shape learning through cognitive, affective, and social processes (Schneider et al., [2022](#)). Three sources of self-efficacy are particularly relevant here. First, guided construction and manipulation tasks can provide mastery experiences, because students complete geometric tasks, observe the consequences of their actions, and progressively tackle more demanding problems. Second, teacher demonstrations of dynamic constructions can provide vicarious experiences that allow students to judge their own capability to perform similar tasks. Third, teacher feedback and encouragement during exploration can provide verbal persuasion. The immediate visual feedback of dynamic manipulation may strengthen all three by linking students' actions to observable mathematical relationships. In the present study, these mechanisms serve as a theoretical rationale rather than as empirically tested mediators.

Gender adds a further dimension to the evaluation of technology-enhanced instruction. Gender differences in mathematics self-efficacy have been documented among secondary school students, particularly among older girls (Mozahem et al., [2021](#)), and access to information and communication technology may relate differently to the mathematics performance of male and female students (Salami & Spangenberg, [2024](#)). It is therefore important to establish whether an instructional innovation benefits male and female students equally. Studies of GeoGebra in circle geometry, however, have focused on overall achievement and understanding and have rarely examined whether gender moderates the instructional effect (Akpape et al., [2026](#); Mollakuqe et al., [2021](#)).

These questions have also gained relevance beyond the face-to-face classroom. Mathematics education has moved rapidly toward digital, blended, and remote modes of learning (Engelbrecht et al., [2020](#); Mulenga & Marbán, [2020](#)), and dynamic geometry applets are among the most portable tools for this transition because they can be shared online, used offline, and embedded in flipped or remote lessons (Ishartono et al., [2022](#); Weinhandl et al., [2020](#)). Evidence on which features of GeoGebra-supported instruction relate to cognitive and affective outcomes in the classroom can therefore inform the design of digital and distance mathematics learning.

In summary, previous studies have examined GeoGebra-supported circle geometry instruction mainly in terms of achievement, whereas studies of self-efficacy have addressed broader mathematics contexts, and the role of gender as a moderator remains largely unexamined. The present study addresses this gap by examining GeoGebra as a digital learning environment for circle geometry among senior secondary school students

in Nigeria. It asks three research questions: (1) Does GeoGebra-supported instruction relate to students' academic performance in circle geometry after controlling for prior performance? (2) Does it relate to students' geometry self-efficacy after controlling for prior self-efficacy? (3) Do these relationships differ between male and female students? By examining cognitive and self-efficacy outcomes within the same intervention and by testing gender as a potential moderator, the study extends research on GeoGebra beyond its predominant focus on overall achievement.

2. Methods

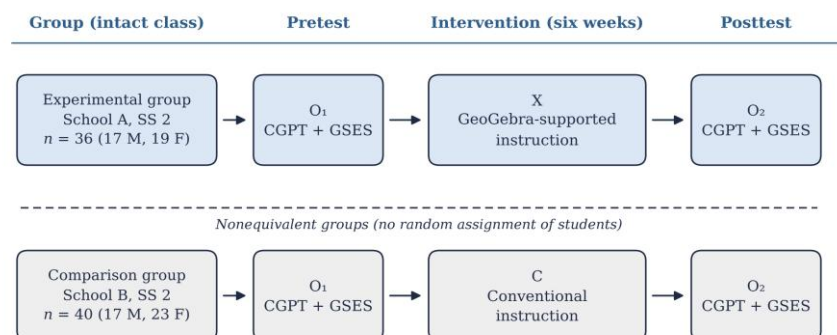
2.1 Research Design

This study employed a quantitative approach with a quasi-experimental, nonequivalent pretest–posttest control group design (Figure 1). Two intact Senior Secondary School Two (SS 2) classes from two different schools were assigned to the instructional conditions: an experimental group that learned circle geometry through GeoGebra-supported instruction (X) and a comparison group that learned the same content through conventional instruction (C). Because the school timetable and class structure did not permit students to be randomly assigned to conditions, existing classes were used as intact groups. Both groups completed the Circle Geometry Performance Test (CGPT) and the Geometry Self-Efficacy Scale (GSES) immediately before the intervention (O_1) and again after the six-week intervention (O_2).

The independent variable was the instructional strategy (GeoGebra-supported vs. conventional instruction), gender was examined as a moderator, and the dependent variables were posttest academic performance in circle geometry and posttest geometry self-efficacy, with the corresponding pretest scores serving as covariates. Several features of the design were intended to reduce threats to internal validity: both groups studied the same curriculum content over the same period, completed identical instruments at both time points, and were compared on posttest scores adjusted for their initial performance and self-efficacy. Nevertheless, because the groups were neither randomly formed nor drawn from the same school, the design supports conclusions about associations rather than strict causal effects, and this limitation is considered when interpreting the findings.

Figure 1

Nonequivalent Pretest–Posttest Control Group Quasi-Experimental Design



O_1 = pretest; O_2 = posttest; X = GeoGebra-supported instruction; C = conventional instruction;
CGPT = Circle Geometry Performance Test; GSES = Geometry Self-Efficacy Scale; M = male; F = female

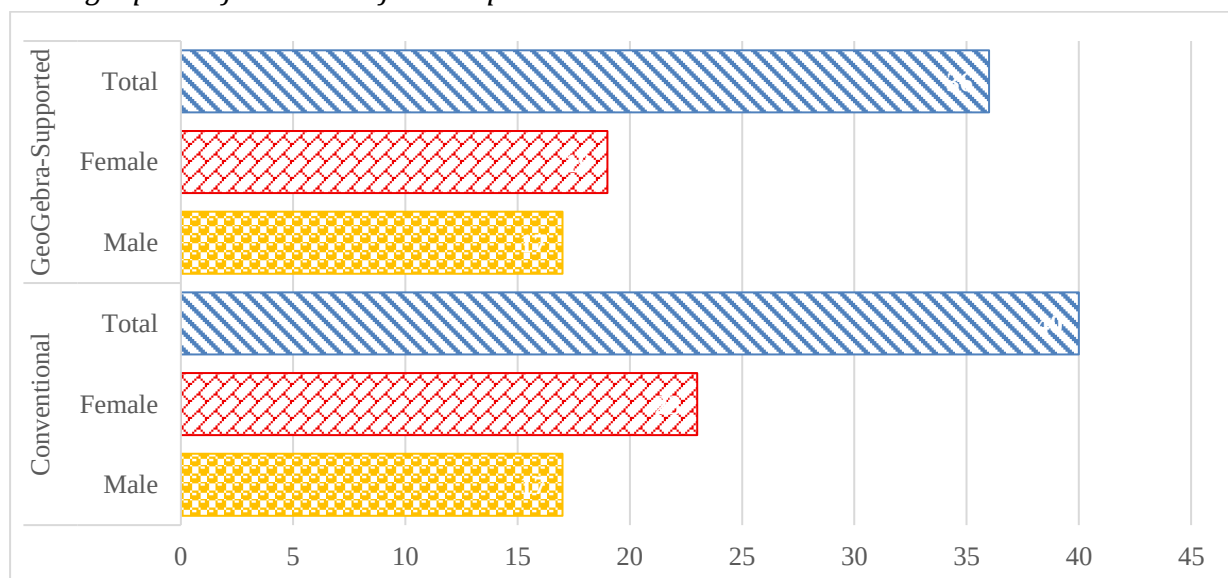
2.2 Participants and Setting

Participants were Senior Secondary School Two (SS 2) students from two public secondary schools in Ekiti State, Nigeria. The two schools were selected purposively because both included circle geometry in their SS 2 mathematics curriculum and because one of them had the computer facilities required for the intervention. The school with adequate ICT facilities was assigned to the experimental condition, and the other school served as the comparison condition. One intact SS 2 mathematics class was drawn from each school. The final sample comprised 76 students with a mean age of approximately 15 years: 36 students (19 female, 17 male) in the GeoGebra group and 40 students (23 female, 17 male) in the conventional group (Figure 2).

The mathematics teacher in the experimental school served as a research assistant and was trained by the researchers before the intervention began. The mathematics teacher in the comparison school taught the same content using the conventional approach. Because each condition consisted of one class from a different school taught by a different teacher, differences between schools, classes, or teachers may have contributed to the outcomes. This limitation is considered when interpreting the findings.

Figure 2

Demographic Information of Participants



2.3 Instruments

Two instruments were used. The Circle Geometry Performance Test (CGPT) was developed to assess students' understanding and application of the circle geometry concepts covered during the intervention, including arcs, radii, chords, and cyclic quadrilaterals. It consisted of 20 multiple-choice items scored dichotomously (1 = correct, 0 = incorrect), yielding a total score between 0 and 20. Sample items included "A chord of a circle is 12 cm long, and the radius of the circle is 10 cm. Calculate the distance of the midpoint of the chord from the centre of the circle" and "The opposite angles of a cyclic quadrilateral are ____."

The Geometry Self-Efficacy Scale (GSES) measured students' perceived capability to perform circle geometry tasks successfully. It was adapted from established principles for

constructing self-efficacy scales and from an existing mathematics self-efficacy measure (Bandura, 2006; Matsui et al., 1990). The adaptation reworded general mathematics statements so that each item referred specifically to students' confidence in performing circle geometry tasks rather than to general mathematics confidence, attitudes, or interest. The scale comprised 10 items rated on a 5-point scale (1 = strongly disagree to 5 = strongly agree), yielding a total score between 10 and 50, with higher scores indicating greater geometry self-efficacy.

Two experts in mathematics education and educational measurement reviewed both instruments for relevance, clarity, alignment with the study objectives, and coverage of the targeted content. Items were revised according to their recommendations before administration. A pilot study was then conducted with 25 students who had characteristics comparable to those of the target participants but were not part of the main sample. Because CGPT items were scored dichotomously, its reliability was estimated with the Kuder–Richardson 20 coefficient ($KR-20 = .78$); the internal consistency of the GSES was estimated with Cronbach's alpha ($\alpha = .81$). Both coefficients indicate acceptable reliability. These coefficients refer to the pilot sample; reliability estimates for the main-study assessments were not available in the reported material.

2.4 Intervention Procedure

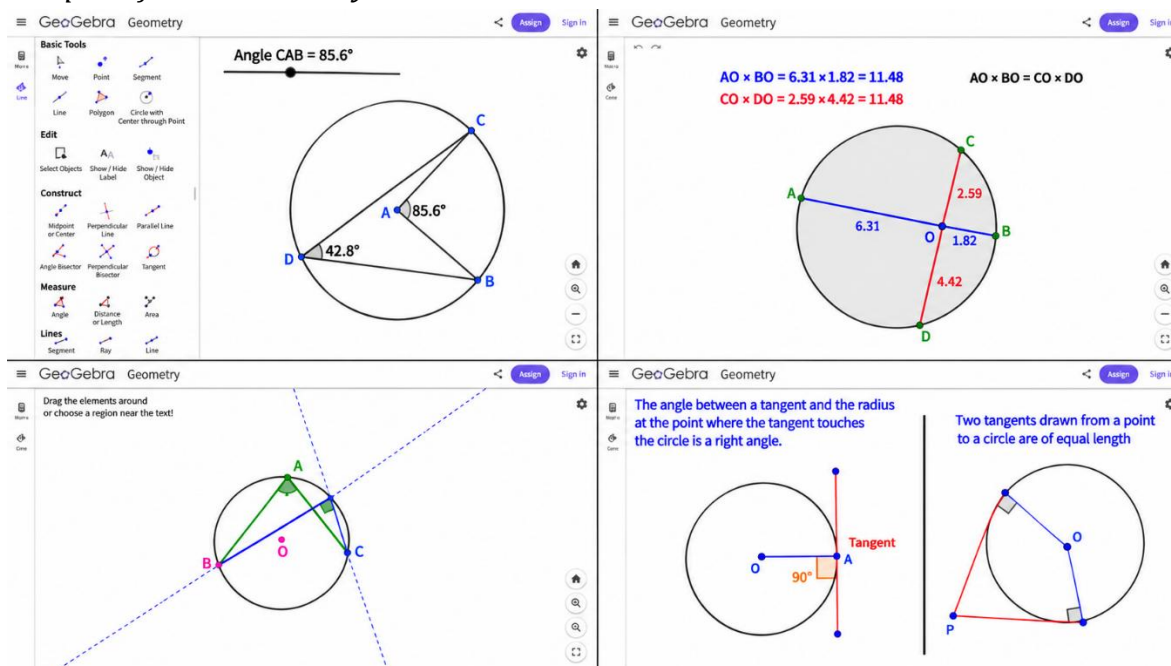
The intervention covered selected circle geometry concepts from the prescribed SS 2 mathematics curriculum and was delivered during regular mathematics lessons over six weeks. Both groups received the same content and the same amount of instructional time. Before the intervention, both groups completed the CGPT and GSES as pretests.

In the experimental group, students learned through GeoGebra-supported activities that combined dynamic visualization, construction, manipulation, and exploration of geometric relationships (Figure 3). Students constructed circles and their associated elements and then moved points to observe how angles, chords, arcs, and related properties changed or remained invariant. The teacher guided each activity with questions and prompts that encouraged students to observe changes, identify patterns, formulate conjectures, and explain the relationships displayed on the screen. Students worked on the computers available in the experimental school, and the lessons combined guided exploration, teacher questioning, class discussion, and individual responses. The researchers trained the teacher in basic GeoGebra operations, the prepared instructional activities, and procedures for guiding students, and they provided a lesson plan for every session to support consistent implementation.

In the comparison group, the teacher explained the same circle geometry concepts, demonstrated procedures on the chalkboard, questioned students, and provided practice exercises. No GeoGebra or other dynamic geometry software was used. The two conditions were thus comparable in content, assessment, and instructional time, and the use of GeoGebra-supported activities was the principal planned difference between them. At the end of the six weeks, both groups completed the CGPT and GSES again as posttests.

Figure 3

Examples of Circle Geometry Activities in GeoGebra



2.5 Data Analysis

Means and standard deviations were used to summarize CGPT and GSES scores by instructional group and gender, and independent-samples t tests were used to examine baseline differences between the groups. Four null hypotheses were tested at the .05 level of significance: GeoGebra-supported instruction is not significantly associated with students' academic performance in circle geometry (H01) or on their geometry self-efficacy (H02), and there is no significant interaction between instructional strategy and gender on academic performance (H03) or geometry self-efficacy (H04). For each outcome, a two-way analysis of covariance (ANCOVA) was conducted with the posttest score as the dependent variable, instructional group and gender as fixed factors, the group-by-gender interaction as an additional term, and the corresponding pretest score as the covariate. The ANCOVA models require linear covariate-outcome relationships, homogeneous regression slopes, and adequately behaved residuals. Detailed diagnostic results were not available in the reported material, so assumption adequacy cannot be established from the summary tables alone.

Effect sizes are reported as partial η^2 for ANCOVA terms and as Hedges' g for unadjusted posttest group differences. The latter describe between-group differences and should not be interpreted as standardized causal effects. The sample comprised 76 students distributed across four group-by-gender cells, which limits sensitivity to small interaction effects. Because each condition consisted of one intact class from a different school, the ANCOVA results were interpreted with attention to potential dependence within classes and to confounding by school and teacher characteristics. Student-level ANCOVA cannot separate the instructional condition from these class-level differences.

2.6 Ethical Clearance

Because the study involved minors, it was subject to ethical review before data collection. Ethical approval was granted by the Research Ethics Committee of the Department of Science Education, Federal University Oye-Ekiti, Nigeria. Permission to conduct the study was also obtained from the authorities of the two participating schools. Parents or guardians provided consent, and students provided assent before participating. Students were informed of the purpose and procedures of the study and of their right to decline or withdraw at any time without penalty. Although the intervention took place during regular mathematics lessons, participation in the research component was voluntary, and students were assured that their decision would not affect their academic standing or classroom treatment. Confidentiality and anonymity were protected throughout, no identifying information is reported in this article, and the data were used solely for research purposes.

3. Results and Discussion

3.1 Results

3.1.1 Baseline Equivalence and Descriptive Statistics

The reported baseline tests did not detect statistically significant differences in circle geometry performance, $t(74) = -0.70$, $p = .484$, $d = -0.16$, or in geometry self-efficacy, $t(74) = 1.62$, $p = .110$, $d = 0.37$, although the GeoGebra group began with a slightly higher and more variable self-efficacy score. Non-significant tests do not establish equivalence, especially in a small, non-randomized sample. Initial scores were statistically adjusted in the ANCOVA models reported below. Table 1 presents students' academic performance by instructional group and test occasion.

Table 1

Descriptive Statistics for Academic Performance in Circle Geometry by Instructional Group and Test Occasion

Group	<i>n</i>	Pretest <i>M</i> (<i>SD</i>)	Posttest <i>M</i> (<i>SD</i>)	Mean gain
GeoGebra-supported	36	5.94 (0.75)	12.92 (1.98)	6.98
Conventional	40	6.07 (0.83)	10.73 (1.92)	4.66

Students in the GeoGebra group improved from $M = 5.94$ ($SD = 0.75$) at pretest to $M = 12.92$ ($SD = 1.98$) at posttest, a mean gain of 6.98 points. Students in the conventional group improved from $M = 6.07$ ($SD = 0.83$) to $M = 10.73$ ($SD = 1.92$), a mean gain of 4.66 points. Both groups therefore improved, but the gain was larger in the GeoGebra group, and the posttest difference corresponded to a large standardized effect (Hedges' $g = 1.11$). Table 2 presents the corresponding results for geometry self-efficacy.

Table 2

Descriptive Statistics for Geometry Self-Efficacy by Instructional Group and Test Occasion

Group	<i>n</i>	Pretest <i>M</i> (<i>SD</i>)	Posttest <i>M</i> (<i>SD</i>)	Mean gain
GeoGebra-supported	36	28.92 (4.16)	32.86 (5.84)	3.94
Conventional	40	27.65 (2.53)	29.00 (2.40)	1.35

Geometry self-efficacy in the GeoGebra group increased from $M = 28.92$ ($SD = 4.16$) to $M = 32.86$ ($SD = 5.84$), a gain of 3.94 points, whereas self-efficacy in the conventional group increased from $M = 27.65$ ($SD = 2.53$) to $M = 29.00$ ($SD = 2.40$), a gain of 1.35 points. The posttest difference corresponded to a large standardized effect (Hedges' $g = 0.87$). The GeoGebra group also showed considerably greater dispersion at posttest ($SD = 5.84$ vs. 2.40), which indicates more heterogeneous responses to the intervention. Tables 3 and 4 disaggregate both outcomes by gender.

Table 3

Academic Performance in Circle Geometry by Instructional Group, Gender, and Test Occasion

Group	Gender	<i>n</i>	Pretest <i>M</i> (<i>SD</i>)	Posttest <i>M</i> (<i>SD</i>)	Mean gain
GeoGebra-supported	Male	17	5.88 (0.60)	13.06 (1.98)	7.18
	Female	19	6.00 (0.88)	12.79 (2.02)	6.79
Conventional	Male	17	6.29 (0.77)	11.35 (2.03)	5.06
	Female	23	5.91 (0.85)	10.26 (1.74)	4.35

Table 4

Geometry Self-Efficacy by Instructional Group, Gender, and Test Occasion

Group	Gender	<i>n</i>	Pretest <i>M</i> (<i>SD</i>)	Posttest <i>M</i> (<i>SD</i>)	Mean gain
GeoGebra-supported	Male	17	28.76 (2.71)	33.00 (6.73)	4.24
	Female	19	29.05 (5.20)	32.74 (5.11)	3.69
Conventional	Male	17	27.76 (3.05)	28.82 (2.43)	1.06
	Female	23	27.57 (2.13)	29.13 (2.42)	1.56

As Table 3 shows, male and female students in the GeoGebra group gained 7.18 and 6.79 points in performance, respectively, compared with 5.06 and 4.35 points for male and female students in the conventional group. Table 4 shows a similar pattern for self-efficacy: male and female students in the GeoGebra group gained 4.24 and 3.69 points, whereas their peers in the conventional group gained 1.06 and 1.56 points. In both groups and for both outcomes, the gains of male and female students were of similar magnitude.

3.1.2 Effect of GeoGebra-Supported Instruction on Academic Performance

Two-way ANCOVA models were used to test the hypotheses. Table 5 presents the results for academic performance.

Table 5

ANCOVA Results for the Effects of Instructional Group and Gender on Academic Performance in Circle Geometry

Source	Type III <i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>p</i>	Partial η^2
Corrected model	112.978	4	28.245	7.750	< .001	.304
Intercept	100.874	1	100.874	27.679	< .001	.280
Pretest CGPT	9.658	1	9.658	2.650	.108	.036
Group	88.971	1	88.971	24.412	< .001	.256
Gender	7.137	1	7.137	1.958	.166	.027
Group $\times$ Gender	1.598	1	1.598	0.439	.510	.006
Error	258.759	71	3.644			
Total	10888.000	76				
Corrected total	371.737	75				

Note. $R^2 = .304$ (adjusted $R^2 = .265$).

The overall model was statistically significant, $F(4, 71) = 7.75$, $p < .001$, and explained 30.4% of the variance in posttest performance ($R^2 = .304$, adjusted $R^2 = .265$). Pretest performance was not a significant covariate, $F(1, 71) = 2.65$, $p = .108$, partial $\eta^2 = .036$; the restricted pretest range may have limited its contribution to the model. Instructional group was significantly associated with posttest performance, $F(1, 71) = 24.41$, $p < .001$, partial $\eta^2 = .256$. Together with the descriptive results in Table 1, this indicates an advantage for the GeoGebra group within the fitted model. H01 was rejected. The association remains conditional on model assumptions and cannot distinguish instruction from school or teacher differences.

3.1.3 Effect of GeoGebra-Supported Instruction on Geometry Self-Efficacy

Table 6 presents the ANCOVA results for geometry self-efficacy.

Table 6

ANCOVA Results for the Effects of Instructional Group and Gender on Geometry Self-Efficacy

Source	Type III SS	df	MS	F	p	Partial η^2
Corrected model	354.326	4	88.581	4.671	.002	.208
Intercept	546.220	1	546.220	28.803	< .001	.289
Pretest GSES	70.313	1	70.313	3.708	.058	.050
Group	226.074	1	226.074	11.921	.001	.144
Gender	0.002	1	0.002	0.000	.993	.000
Group $\times$ Gender	2.355	1	2.355	0.124	.726	.002
Error	1346.450	71	18.964			
Total	73933.000	76				
Corrected total	1700.776	75				

Note. $R^2 = .208$ (adjusted $R^2 = .164$).

The overall model was statistically significant, $F(4, 71) = 4.67$, $p = .002$, and explained 20.8% of the variance in posttest self-efficacy ($R^2 = .208$, adjusted $R^2 = .164$). Pretest self-efficacy was not a significant covariate, $F(1, 71) = 3.71$, $p = .058$, partial $\eta^2 = .050$. This result does not establish baseline equivalence; adjustment remains appropriate to account for initial scores. Instructional group was significantly associated with posttest self-efficacy, $F(1, 71) = 11.92$, $p = .001$, partial $\eta^2 = .144$. Together with Table 2, this supports a higher self-efficacy score for the GeoGebra group within the fitted model, and H02 was rejected. However, the markedly different posttest dispersions require a robust sensitivity analysis before the statistical inference can be considered secure.

3.1.4 Interaction Between Instructional Strategy and Gender

The interaction between instructional group and gender was not significant for academic performance, $F(1, 71) = 0.44$, $p = .510$, partial $\eta^2 = .006$ (Table 5), or for geometry self-efficacy, $F(1, 71) = 0.12$, $p = .726$, partial $\eta^2 = .002$ (Table 6). H03 and H04 were therefore not rejected. The descriptive results in Tables 3 and 4 show gains for both male and female students in each condition. These findings do not demonstrate equivalent benefits across genders: the small cell sizes and the two-class design limit the ability to detect moderation, and smaller differences cannot be ruled out.

3.2 Discussion

The first main finding is that students who learned in the GeoGebra-supported environment achieved higher adjusted posttest performance in circle geometry than students who received conventional instruction. This finding is consistent with studies that have associated GeoGebra-supported instruction with higher achievement in geometry and other areas of secondary mathematics (Akpage et al., 2026; Birgin & Topuz, 2021; Mollakuqe et al., 2021; Mosese & Ogbonnaya, 2021; Zulnaldi et al., 2020) and with meta-analytic evidence on the benefits of dynamic geometry for spatial visualization (Suparman et al., 2024). A plausible explanation lies in the nature of circle geometry itself. Relationships among radii, chords, arcs, and angles are difficult to convey in static diagrams, whereas dragging and linked representations allow students to see which relationships remain invariant and why (Greefrath et al., 2018; Kusumah et al., 2020; Ziatdinov & Valles, 2022). The unadjusted posttest difference (Hedges' $g = 1.11$), however, is larger than the average effect of dynamic mathematics software reported in a recent three-level meta-analysis ($d = 0.63$; Ji et al., 2024). This pattern is consistent with the tendency of small quasi-experiments with few participating classes to produce larger effects, and it underscores the need for replication with more classes and schools (Hillmayr et al., 2020).

The performance finding is also meaningful in context. Geometry remains conceptually challenging for many secondary school students, and these difficulties can be reinforced when teaching relies mainly on static representations and teacher-directed explanation (Dahal et al., 2022; Hassan et al., 2023). The present study shows that a dynamic representational environment can be integrated into regular lessons in a public school setting, which is consistent with evidence that GeoGebra can be used meaningfully in disadvantaged classrooms when teachers are supported (Manganyana et al., 2020).

The second main finding is that the GeoGebra group reported higher geometry self-efficacy after controlling for initial self-efficacy. This result agrees with studies that have linked GeoGebra-based instruction with higher self-efficacy and self-regulated learning (Ishartono et al., 2022; Zetriuslita et al., 2021) and with positive changes in motivation and attitudes (Kassa et al., 2025; Romero & García, 2024). It contrasts, however, with the finding that a mobile mathematics application left self-efficacy largely unchanged despite gains in achievement (Mamolo & Sugano, 2024). One interpretation is that the opportunity to act on mathematical objects, rather than digital delivery as such, supports efficacy beliefs. From a social cognitive perspective, manipulating geometric objects, observing the consequences, and solving increasingly demanding tasks may provide the mastery experiences that build perceived capability (Bandura, 1986, 2006; Schunk & DiBenedetto, 2020). Because these experiences were not measured directly, they remain a plausible explanation rather than an established mechanism.

The concurrent advantage in performance and self-efficacy is noteworthy because the two outcomes tend to reinforce each other over time (Arens et al., 2022; Matsui et al., 1990). An instructional environment that allows students to experience mathematical relationships directly may therefore strengthen both what students can do and what they

believe they can do. Two qualifications apply. First, the study did not test whether self-efficacy mediated the relationship between instructional strategy and performance. Second, the larger posttest dispersion in the GeoGebra group indicates heterogeneous posttest scores; it does not by itself establish individual differences in gains, a pattern that future studies could examine by measuring the sources of self-efficacy directly.

The third main finding is that no interaction between instructional strategy and gender was detected for either outcome. This finding is relevant because gender gaps in mathematics self-efficacy have been documented among secondary school students (Mozahem et al., 2021), and access to technology may relate differently to the performance of male and female students (Salami & Spangenberg, 2024). Both male and female students showed descriptive gains, but access to the software and students' experiences of using it were not measured separately by gender. This result does not imply that technology-enhanced geometry instruction is gender-neutral in all contexts. Because the sample and group-by-gender cell sizes were small, small gender-related differences in responsiveness cannot be excluded.

Although the intervention was implemented face to face, its design features have direct implications for digital and distance mathematics education. The core learning activity, namely constructing, dragging, and observing invariant relationships in GeoGebra applets, does not depend on the physical classroom and can be delivered through shared online applets, virtual classroom tools, or offline installations in low-connectivity settings (Mulenga & Marb  n, 2020; Weinhandl et al., 2020). GeoGebra-integrated flipped and online learning can also support self-regulated learning when students work independently (Ishartono et al., 2022), and dynamic mathematics software tends to be more effective when students use it themselves rather than only observe teacher demonstrations (Ji et al., 2024). The teacher prompts used in this study, which asked students to observe, conjecture, and explain, could be translated into embedded questions or discussion tasks in asynchronous environments. These possibilities nevertheless require direct empirical testing in blended and fully remote settings (Engelbrecht et al., 2020).

Several limitations qualify the findings. First, each condition consisted of a single intact class from a different school taught by a different teacher, so the instructional condition is confounded with school, teacher, and the availability of ICT facilities. The ANCOVA models also treated students as independent despite their nesting within classes, which may have underestimated standard errors. Second, the intervention lasted six weeks and no delayed posttest was administered, so the durability of the observed advantages is unknown. Third, the GSES was a brief adapted scale whose factor structure was not examined, and pretest CGPT scores showed a restricted range. Main-study reliability coefficients and detailed ANCOVA diagnostic results were also unavailable in the reported material, and the unequal self-efficacy dispersion requires robust verification. Fourth, the sample size limited the power to detect small interaction effects. Future studies should assign multiple classes or schools to conditions, use multilevel models, include delayed posttests, measure the sources of self-efficacy directly, examine

teacher professional development as a condition for implementation quality (Thurm & Barzel, 2020), and test the same activities in blended and remote learning environments.

4. Conclusion

This study examined GeoGebra as a digital learning environment for circle geometry. After controlling for initial scores, students who learned with GeoGebra-supported activities achieved higher adjusted posttest scores in both academic performance and geometry self-efficacy than students who received conventional instruction. Dragging, construction, and linked visual representations allow students to examine how geometric relationships change while the underlying properties remain invariant, so that circle theorems can be investigated dynamically rather than only memorized from static diagrams. No interaction between instructional strategy and gender was detected, but this does not establish equivalent benefits for male and female students; small differences cannot be ruled out.

Because the study compared two intact classes from different schools and did not include a delayed posttest, the findings should be read as associations rather than as definitive evidence of causal or lasting effects, and they should be generalized with caution. Within these limits, the results support the purposeful use of GeoGebra as a complement to conventional instruction for geometry topics that benefit from visualization and exploration. Teachers can use guided GeoGebra explorations to support both learning and students' confidence in solving geometry problems. Teacher education institutions should provide practical professional development in designing GeoGebra-supported lessons for face-to-face, blended, and online formats (Thurm & Barzel, 2020). Where devices are scarce, shared computers, teacher-led projection, and offline use of GeoGebra offer feasible alternatives. Finally, the design principles of the intervention, namely dynamic exploration, guided conjecturing, and immediate visual feedback, are transferable to blended and remote learning environments, where they warrant further investigation.

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Author Contributions

Oluwanife Segun Falebita: Conceptualization, Methodology, Formal analysis, Visualization, Writing – original draft, Writing – review & editing, and Project administration.

Joseph Oluwatosin Fadipe: Investigation, Data curation, Resources, Validation, and Writing – review & editing. Both authors have read and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

AI Use Disclosure

During the preparation of this manuscript, the authors used Claude (Anthropic) to assist with language editing, literature searching, reference identification, and citation formatting. All AI-assisted content was reviewed and verified by the authors, who take full responsibility for the accuracy, integrity, and final content of the manuscript. No AI tool is listed as an author or co-author. ChatGPT (OpenAI) was subsequently used to assist with language editing, consistency checking, and identifying reporting gaps. Any proposed changes require author verification against the original records and statistical outputs.

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