

Effects and Perceptions of Teaching Geometry through GeoGebra Modelling Approach on Students' Learning Outcomes in TVET Schools in Tamale, Ghana

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Abstract

This study investigated the effects and perceptions of teaching geometry through the GeoGebra Modelling Approach in Technical and Vocational Education and Training (TVET) schools within the Tamale Metropolis of Ghana. Using a Quasi-experimental design with interviews, the study involved 40 second-year students from two intact classes, with each class comprising 20 students. Data were collected through achievement tests and interviews. The findings revealed that students taught using GeoGebra Modelling achieved significantly higher post-test scores, indicating deeper conceptual understanding and stronger problem-solving skills ($F(1, 37) = 16.795$, $\eta^2 = 0.312$, $p = 0.00$), with a large effect size. It also promotes interactive learning and supports digital integration in mathematics instruction. The study recommends the use of GeoGebra

modelling-based pedagogy to improve mathematics teaching and learning outcomes in Ghana's TVET institutions.

Keywords: GeoGebra Modelling Approach, Geometry Performance, Mathematics Education, TVET Students, Technology-Enhanced Learning, Geometry Instruction, Tamale Metropolis

1. Introduction

Globally, the effective teaching of mathematics is key to the development of a nation in terms of science, technology and economic development. However, students' difficulties in learning Geometry, a fundamental mathematical concept, have been related to the conventional teacher-centered learning approach where rote learning is performed, and the students are unable to think mathematically (Madimabe, 2020). The embedding of digital tools (such as GeoGebra) has become a pedagogically innovative approach in mathematics education (Rabi et al., 2021). The review of the literature reveals that GeoGebra's visual and dynamic characteristics are effective in enhancing academic performance as well as motivation and engagement in mathematics learning (Jelatu et al., 2018; Khansila et al., 2022).

GeoGebra, a dynamic software environment that integrates Geometry, Algebra, and Calculus, enables students to interact with mathematical representations, thereby enhancing their conceptual understanding and problem-solving skills (Zutaah et al., 2023). Shadaan and Leong (2013) reported that students who learned using GeoGebra performed significantly better in the learning of geometry than students who learned geometry using conventional methods. Moreover, the findings by Zulnadi, Oktavika and Hidayat (2020) indicated that the instruction using GeoGebra was able to positively affect students' mathematical achievement and motivation. Likewise, Uwurukundo et al. (2020) found that students' achievement in mathematics lessons increased, and they became more involved when they used GeoGebra. It is concluded that the use of GeoGebra has a positive effect on students' mathematics learning outcomes based on empirical studies reported. Although the pedagogical potential of technology in mathematics classroom is immense, Technical and Vocational Education and Training (TVET) is especially valuable when it comes to the modelling approach.

Modelling approach is used to relate real world to mathematical abstraction by developing, testing and refining model activities to achieve conceptual depth and critical thinking (Salha & Qatanani, 2021). The GeoGebra Modelling Approach applies the following principles: cognitive constructivist principles, and mastery learning frameworks (Ayamah et al., 2020), which require learners to visualise, mathematise and validate Geometric relationships. For example, Küçük and Gün (2023) found that the use of the GeoGebra modelling teaching method positively affected the spatial reasoning, conceptual understanding, and perceptions of the students towards geometry.

In Technical and Vocational Education and Training (TVET), visualisation and applied reasoning are highly relevant when acquiring skills, in which applied challenges are especially prominent. The use of GeoGebra in TVET contexts shows a transition towards education that focuses on: learner centered, technology and skills oriented, and responsive to the 4th Industrial Revolution (Hussin, 2018). TVET students learn Geometric concepts and apply them in day-to-day practice to carpentry, welding, construction and designing.

In a Ghanaian context, many mathematics teachers are not well trained and confident to apply technology in their classroom teachings, reducing innovation and engagement of learners (Ansah et al., 2022; Atteh et al., 2020). A few of the mathematics teachers use digital tools such as GeoGebra to help them to link theory with practice, to deepen their conceptual understanding and develop their skills.

The study is of significance for bridging the gap between the abstract geometric mathematical theory and its application in the real world, particularly for learners from the TVET who are involved in practices that require them to use geometric reasoning in their practical work. Although there are some challenges with teacher preparation and resources, the overall results of this collective research clearly support the use of GeoGebra modelling as an innovative pedagogical tool to enhance the learning outcomes of geometry in mathematics education in Ghana and other related contexts.

This study is focused on the following research questions:

1. What effect does the GeoGebra Modelling Approach have on TVET students' learning outcomes in geometry?
2. What are TVET students' perceptions of using the GeoGebra Modelling Approach to solve geometry problems?

This study addresses these questions and adds to the existing knowledge of technology supported learning in mathematical modelling in mathematics education. It would offer practical lessons for teacher education programmes, curriculum designers and policy makers who are interested in the use of digital tools in teaching mathematics in the Ghanaian TVET institutions. Last but not least, the results show that the GeoGebra Modelling Approach not only would enhance students' academic attainment, but would also modernize the way they are taught, ensuring that 21st century skills in problem-solving would be developed in students to equip them for technical and vocational excellence.

Also, the concept of Technological Pedagogical Content Knowledge (TPACK) has become pivotal in the current pedagogical discourse about mathematics. To successfully integrate technology, teachers need to know how content, pedagogy, and technology work together to promote meaningful learning (Jibril & Adedokun-Shittu, 2024). Teacher professional development programmes with GeoGebra have contributed to an increase in confidence, creativity, and quality of teaching in different settings such as Nepal and Taiwan (Uwurukundo et al., 2020). Yet in Ghana, such problems as the lack of digital

resources, training and use of conventional methods remain a hindrance to the effective use of technology (Brown-Joseph, 2010).

Research has shown the positive effects of technology in students' mathematical thinking, spatial visualisation and problem-solving abilities in a consistent manner (Alkhateeb, 2019). Algebraic, geometric and graphical representations are offered by GeoGebra so that learners can try, predict and verify the solutions to achieve higher-order thinking (Simbolon & Siahaan, 2020). In addition to learning outcomes, students become more satisfied and mathematics is more positively perceived when they are on dynamic digital devices rather than when they are involved in Conventional teaching (Lavicza, 2010; Moeller & Reitzes, 2011).

However, there are some longstanding difficulties in the use of technology in mathematics instruction that are mentioned in the literature. TPACK training and institutional support for teachers is often inadequate to fully make use of digital tools. Some students also encounter challenges in using the software initially, but these challenges reduce as they are guided through and explore the software (Gatete, 2026). In addition, in many developing settings, access to education, infrastructure and teacher readiness are obstacles.

Nevertheless, using GeoGebra in Geometry education is a great step towards constructing inquiry-based learning. The study highlights its ability to revolutionise the teaching of difficult concepts like circle geometry and 3D shapes, transferring rote learning to conceptual understanding and active exploration (Adelabu et al., 2022; Murni & Jehadus, 2019).

Although previous studies have reported positive effects of GeoGebra on students' mathematical achievement, spatial reasoning, motivation, and conceptual understanding, much of this evidence has been generated in general mathematics education rather than in TVET contexts. Consequently, there remains limited empirical evidence concerning how GeoGebra-supported mathematical modelling can be used to develop geometry learning among TVET students, particularly within the Ghanaian educational context. This gap is important because TVET students are expected to apply mathematical knowledge to practical and occupational tasks in which spatial reasoning, measurement, visualisation, and problem-solving are central. Moreover, existing studies have tended to examine either learning outcomes or students' attitudes toward technology, rather than considering both dimensions within a single instructional intervention. The present study therefore investigates the effect of the GeoGebra Modelling Approach on TVET students' geometry performance and examines their perceptions of using the approach to solve geometry problems.

2. Theoretical Background

The mathematical modelling capability is considered the ability to move independently yet insightfully through the various phases of the modelling process in a problem situation that is contextualised (Blomhøj & Jensen, 2003). This process is cyclical and reflective as described in Figure 1. It starts by recognising constraints and necessary conditions in a real-world context, then simplifying and idealising the problem to a mathematically tractable situation. The second step is to re-formulate the actual problem into a mathematical model, to create a solution based on the mathematical tools and theories and to explain and check the solution against the real problem (Maaß, 2006; Swetz, 1991).

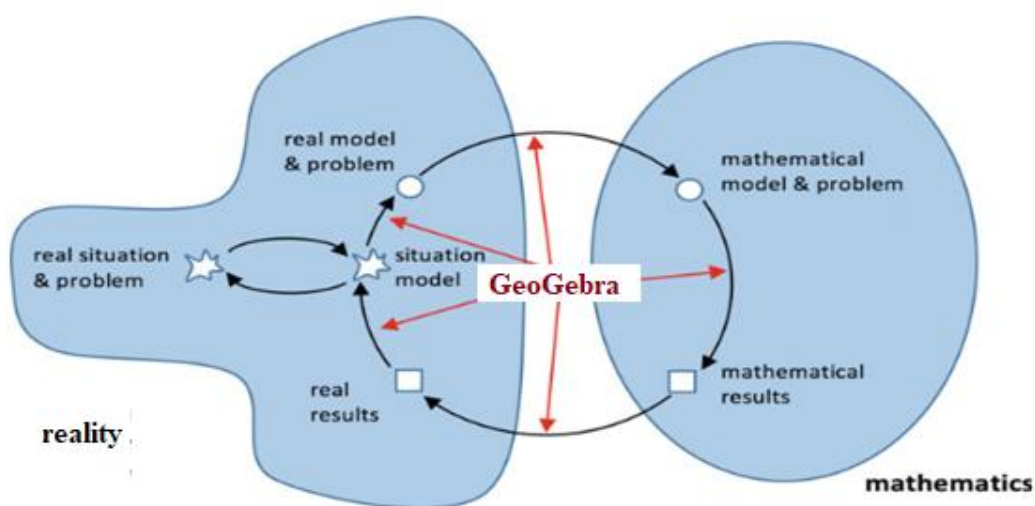


Figure 1. Adapted Modelling Cycle with the digital tool GeoGebra (Greefrath & Siller, 2018, p. 364)

Digital tools are critical to solve significant mathematical modelling problems and modelling skills are strongly related to the development of these skills. These tools can be integrated at multiple stages of the modelling cycle, enhancing learners' interpretation, visualisation, and analytical skills. Making well-informed decisions about which tools, such as GeoGebra, to use

significantly improves student engagement and conceptual understanding (Blum & Leiss, 2007; Cevikbas, Greefrath, & Siller, 2023).

Digital tools serve as an integrated representation medium that enhances students' comprehension during the modelling process. Consequently, Greefrath and Siller (2018) outlined two major categories of action: utilising digital tools and applying them across the stages of the modelling cycle, as shown in Figure 1.

Mathematical modelling is a key tool for the conversion of real-life situations into mathematical models. Mathematical representations that allow learners to understand, interpret and solve complex problems (Vorhölter et al., 2019). The modeller starts by defining the problem in the real world, simplifying the problem, and identifying variables and parameters. These variables are used in a mathematical model by means of mathematical relationships in the form of equations. Then technology is introduced to enable quick calculations, visualisation and interactive exploration, such as GeoGebra. GeoGebra is a medium that promotes dynamic experimentation, makes students more aware of their metacognition, and boosts 21st-century skills. Geometry has a predominant role in this process since real world phenomena frequently consist of geometric forms. Solid geometry is an important component of the mathematics curriculum and deals with shapes such as prisms, cones, cylinders, and pyramids. This study investigates how this is reflected in the study. The research explores the potential of using GeoGebra modelling in the classroom of TVET in improving students' understanding, problem-solving ability and performance in geometry. GeoGebra is efficient and engaging in learning. Students can see abstract concepts and can avoid difficult manual calculations. Mathematics educators, on the other hand, enjoy the benefit of saving instruction time and making classroom interactions more effective. Zulnaidi et al. (2020) concluded that Geometry learning using GeoGebra was meaningful and accessible as it allows for active exploration.

3. Conceptual Framework

The conceptual framework illustrates the relationship among the variables: the GeoGebra Modelling Approach, effects on GeoGebra learning, perceptions of using the GeoGebra modelling approach, and Geometry learning outcomes as presented in Figure 2.

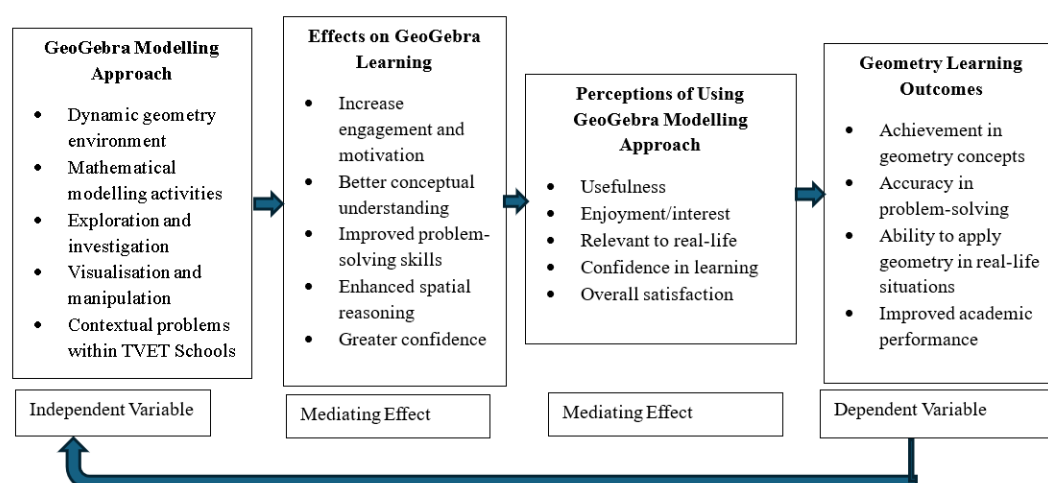


Figure 2. Relationship between the GeoGebra Modelling Approach and Students' Geometry Learning Outcomes.

Source: Authors' construct (2026)

The conceptual framework proposes that the GeoGebra Modelling Approach serves as the independent variable that influences students' geometry learning. Through dynamic visualisation, mathematical modelling, exploration, manipulation of geometric objects, and engagement with real-life problems, the approach is expected to improve students' understanding of geometry and their ability to apply geometric concepts.

The effects on geometry learning and students' perceptions of using the GeoGebra Modelling Approach function as important intervening factors in this relationship. Positive experiences, such as increased engagement, motivation, conceptual understanding, confidence, and problem-solving ability, may strengthen the effectiveness of the approach. Similarly, favourable perceptions regarding GeoGebra's usefulness, ease of use, enjoyment, relevance, and overall satisfaction may encourage students to participate more actively in learning activities.

Ultimately, these interactions are expected to influence geometry learning outcomes, which constitute the dependent variable. Improved learning outcomes may be reflected in higher achievement, better problem-solving accuracy, stronger spatial reasoning, greater ability to apply geometry in real-life contexts, and improved higher-order thinking skills. Thus, the framework assumes that the use of GeoGebra modelling can directly and indirectly contribute to improved geometry learning outcomes through its effects on students' learning experiences and perceptions.

4. The Significance of the Study

Current studies of geometry teaching focus on establishing effective teaching in powerful theoretical and conceptual frameworks that account for the development of mathematical sense-making in learners and the mediation of this development by teachers using technology. Geometry is a fundamental branch of mathematics that demands a high level of spatial reasoning, abstraction, and modelling skills, which are highly dependent on teachers' pedagogical content knowledge and their highest level of professional preparation.

Although the idea is promising, literature has pointed to a number of issues that could impede the widespread adoption of this approach. These comprise limited access to computers and Internet connectivity, no technical support and lack of alignment of the curriculum (Akaazua et al., 2017; Tay & Wonkyi, 2018). Further, teachers see technology as an additional burden, instead of an instructional aid. Addressing these challenges will involve ongoing investment in ICT infrastructure, ongoing teacher professional development, and embedding digital skills in teacher education programmes.

In the first place, Bukari and Govender (2024) suggested technology integration into mathematical modelling and this current study fills this gap by incorporating GeoGebra as a modelling approach in the TVET schools in Ghana. Second, the majority of studies were done on mainstream secondary school contexts, while a few studies focused on the effectiveness of GeoGebra in Technical and Vocational Education and Training (TVET) geometry classes. Third, while research like that of Küçük and Gün (2023) focused on students' attitudes towards GeoGebra, the perception of the GeoGebra Modelling Approach in learning geometry concerning TVET students is less studied. Hence, the present study aimed at tackling the gaps and investigated the effects and perceptions of teaching Geometry using the GeoGebra Modelling Approach on students' geometry learning outcomes in the TVET schools in the Tamale Metropolis, Ghana.

5. Methodology

The study employed a quasi-experimental pre-test–post-test comparison-group design, supplemented by semi-structured interviews to obtain qualitative data on students' perceptions of the GeoGebra Modelling Approach.

Overall, the methodology adopted was rigorous to scrutinise the instructional effectiveness of GeoGebra as a modelling tool for Geometry learning in TVET; and it gave empirical and contextual understanding of the potential use of GeoGebra to improve the mathematical understanding and problem-solving ability of the students in TVET contexts. The methodology was based on a practical activity demonstrating how the theory and conceptual framework worked together to achieve the study's goal.

5.1. Practical Modelling Activity: Designing and Evaluating a Septic Tank Using GeoGebra

A practical modelling task involving the design of a septic tank was used to illustrate how GeoGebra mediated students' mathematical activity in a TVET Building and Construction context. Students were presented with the mathematical modelling problem: A construction project requires a rectangular septic tank with a minimum capacity of 12 m³. The available construction area limits the tank to a maximum length of 4 m and width of 2.5 m, while the maximum permissible depth is 1.5 m. Determine suitable dimensions for the tank and justify your design.

5.2. Mathematical Model

Let:

- L = length of the tank
- W = width of the tank
- D = depth of the tank
- Required minimum volume = 12 m³

The volume of a rectangular tank is:

$$V = L \times W \times D$$

Therefore, the design must satisfy:

$$LWD \geq 12$$

subject to:

$$L \leq 4, W \leq 2.5, D \leq 1.5$$

A suitable choice is:

$$L=4\text{m}, W=2\text{m}, D=1.5\text{m}$$

Thus,

$$V=4 \times 2 \times 1.5=12\text{m}^3$$

5.3. Justification of the Design

The proposed dimensions of 4 m × 2 m × 1.5 m provide exactly the required minimum capacity of 12 m³. The length and width remain within the available construction limits, and the depth does not exceed the maximum permissible depth. Therefore, the design is feasible and satisfies all the stated constraints.

5.4. Connection to GeoGebra Modelling

In GeoGebra, students vary L , W , and D using sliders while observing how changes in each dimension affect the tank's volume. They can investigate questions such as:

- What happens to the volume when the depth is reduced?
- What combinations of length and width produce at least $12m^3$?
- Which dimensions provide the required capacity while using the available space efficiently?

This allows students to move from a *real-life construction problem* → *mathematical representation* → *dynamic exploration* → *solution* → *justification*, illustrating how the GeoGebra Modelling Approach can support geometry learning and problem-solving skills.

5.5. Participants

This study included a total of 40 second year students from two Technical and Vocational Education and Training (TVET) institutions in the Tamale Metropolis of Ghana. These were purposively chosen to ensure their accessibility, availability of participants, and students' willingness to participate in this study.

Two intact classes were randomly selected, one from each of the two Technical and Vocational Education and Training (TVET) schools were included in the study. 20 students participated in each class and there were 40 students. A class was designated as a "control group" to be compared in a balanced way with the "experimental group". Class assignment to groups was based on students' pre-test scores. Initial group comparability was confirmed by an independent samples t-test. The classes with lower mean pre-test scores were selected as the experimental group, who were taught using the GeoGebra Modelling Approach. The other class was the control class and was taught in the conventional way.

Each participant was assigned to his/her own school, and within each school the participants were assigned based on the school's own technique, with all eligible students having equal opportunity of participating. This was done to reduce selection bias and increase the internal validity of the study. The sample size was deemed to be sufficient for an intensive classroom intervention, monitoring, and detailed assessment of learning outcomes in a quasi-experimental teaching and learning environment.

Students were all taking courses in geometry in the TVET mathematics curriculum and had similar instructional exposure prior to the intervention. The intervention was carried out for eight (8) weeks with three meetings per week for both the control and the experimental groups.

5.6. Data Collection

Pre-test, post-test and interviews were taken as data collection tools. The following data types were collected to assess the effectiveness and perceptions of the GeoGebra Modelling Approach on students' geometry learning outcomes in the TVET schools in Tamale Metropolis in Ghana.

5.7. Quantitative Data

The quantitative data were collected using pre-test and post-test in geometry achievement test of experimental and control group students. The pre-test was used as a baseline equivalent and to identify students' entry-level knowledge of the geometry concepts in the curriculum, plane and solid geometry and problem-solving tasks. For quantitative data a sample of 40 students was taken.

The post-test was conducted after the 8 weeks of instructional intervention for both experimental and control group in a standardised manner. The post-test was composed of six (6) conceptual, procedural, and problem-solving questions related to geometry content areas presented during the intervention and was also theory-based. The test was designed to capture the content and function of the four (4) content based theory questions employed in the pre-test and thus allow for comparison of students' learning gains.

In order to make the test valid, the Geometry Achievement Test was constructed based on the purpose of the study and topics of geometry in the study of TVET mathematics curriculum. Test items were checked by experts in mathematics education, measurement and evaluation, and experienced mathematics teachers to determine their relevance, clarity and appropriateness. Recommendations and suggestions made by them were taken into the final version of the instrument.

A structured marking scheme was used to mark students' answers, focusing on conceptual understanding and correctness of procedure. The scores obtained were statistically analysed using descriptive and inferential statistics to find out differences in performance due to the instructional method.

5.8. Qualitative Data

Semi-structured interviews were conducted with students in the experimental group to gather qualitative data. The responses obtained from the interviews were used to document students' learning process, involvement and perceptions of the GeoGebra Modelling Approach. The twenty (20) students were put into four (4) groups of five (5) for the interview. The interview guide was pre-tested with experts in mathematics education and mathematics research methodology to ensure the validity and trustworthiness of the qualitative data, in terms of relevance, dependability, confirmability, transferability, and clarity of the questions. Additionally, member checking was used which allowed participants to read and confirm their interview responses so that their opinions and experiences were represented correctly.

All interviews were conducted with the informed consent of the interviewees and audio-recorded and subsequently transcribed verbatim. Interviews were carried out in a non-threatening and familiar setting to allow the participants to give their

opinions freely and honestly. Further, the time spent with participants during the intervention period served to build rapport and ensure the collection of rich and authentic data, as well as trustworthiness. Moreover, the open-ended, semi-structured interview questions enabled participants to share detailed information regarding their experiences, which deepened and strengthened the results obtained. The thematic analysis was used to analyse the qualitative data, which was coded and themed systematically and related to the research question to ensure consistency and meaningful interpretation of participants' responses. A combination of quantitative and qualitative information was used to improve the rigor of analysis and to give a more complete picture of the instructional effectiveness of the intervention.

6. Data Analysis

Appropriate statistical and analytical techniques were used to analyse the collected data in relation to each of the research questions.

Research Question One: What effect does the GeoGebra Modelling Approach have on TVET students' learning outcomes in geometry?

To answer this research question, the pre-test and post-test scores of the students were summarised by inferential statistics. To determine if there were any significant differences between the experimental and control groups at the pre-test, an independent samples t-test was conducted. Analysis of Covariance (ANCOVA) was used to investigate the effect of GeoGebra Modelling Approach on the students' post-test achievement after controlling pre-test scores. Research Question Two: 2. What are TVET students' perceptions of using the GeoGebra Modelling Approach to solve geometry problems?

The semi-structured interviews yielded qualitative data, which was analysed through thematic analysis. Audio recordings from interviews were verbatim transcribed, coded, and sorted into meaningful categories. Codes were then clustered into themes based on students' perceptions and experiences of the GeoGebra Modelling Approach. Representative quotations from the participants were included to provide support to the themes identified where suitable.

7. Results

To answer Research Question 1, a two-stage analytical approach was used to assess the effect of the GeoGebra Modelling Approach on students' Geometry learning outcomes, considering their prior achievement.

Baseline descriptive statistics were analysed to determine baseline Geometry proficiency prior to the intervention,

Table 1. Group Statistics for Pre-Test Scores in School A and School B

Group Statistics	TVET Schools	N	Mean	Std. Deviation	Std. Error Mean
Pre-test Scores	School A	20	54.45	14.310	3.200
	School B	20	53.85	14.199	3.175

The result showed that the mean pre-test score and the score dispersion of the experimental group (School A) and the control group (School B) were comparable, indicating a pre-treatment initial group comparability.

Secondly, an independent samples t-test was conducted to statistically examine pre-intervention equivalence (Tables 2 and 3).

Table 2. Levene's Test Results for Geometry Pre-test Scores

Group	F	df	P-value
Pre-test Scores	0.02	38	0.963

Levene's test confirmed homogeneity of variance, while the t-test revealed a statistically detectable difference in pre-test performance between the groups. This outcome indicated that baseline differences in prior Geometry knowledge could potentially confound post-test comparisons if not statistically controlled.

Consequently, Analysis of Covariance (ANCOVA) was employed as the primary inferential technique to isolate the effect of the GeoGebra Modelling Approach on post-test geometry performance while adjusting for pre-test scores.

Table 3. Independent Samples T-test of Pre-test Scores of Sampled Schools

Group	N	Mean	SD	F	t-value	Df	P-value
School A	20	54.45	13.310	0.02	0.133	38	0.043
School B	20	52.85	14.199				

The results in Table 2 of the pre-test scores for Geometry achievement were statistically significant [$t(38) = 0.133$, $p = 0.043$]. It was therefore concluded that there was a statistically significant difference between School A and School B regarding students' pre-test scores of the geometry achievement test before treatment.

Table 4. ANCOVA Results on Geometry Modelling Scores Obtained by Students in both Groups

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Observed Power
Corrected Model	1285.258	2	642.629	9.386	.001	.337	.969
Intercept	10432.708	1	10432.708	152.384	.000	.805	1.000
Pre-test scores	118.858	1	118.858	1.736	.196	.045	.250
Group	1149.840	1	1149.840	16.795	.000	.312	.979
Error	2533.142	37	68.463				
Total	209454.000	40					

The ANCOVA results showed a statistically significant effect of instructional group on post-test performance, $F(1, 37) = 16.795$, $p = 0.00$, with a large effect size (Partial $\eta^2 = 0.312$). This finding demonstrates that, after controlling for prior achievement, students exposed to the GeoGebra Modelling Approach achieved significantly higher Geometry scores than those taught using the conventional method.

Overall, the convergent evidence from inferential statistics, pre-test equivalence testing, and covariate-adjusted analysis provides strong empirical support that the GeoGebra Modelling Approach has a significant positive effect on the geometry learning outcomes of TVET students, with an observed power of 97.9%.

The inferential results from the ANCOVA support the results derived from the inferential analysis and show a clear and meaningful performance advantage for the experimental group over the control group. The consistency and higher central tendency of students' score distributions, as well as the improvement in the score distribution using GeoGebra in comparison to the conventional method, are convincing evidence that the geometry achievement of TVET students can be improved through the modelling approach.

8. Analysis of Interview Results

Thematic analysis was used to analyse qualitative data from the semi-structured interviews conducted to answer Research Question 2. By using this analytical approach, students' experiences and perceptions towards the GeoGebra Modelling Approach in the teaching and learning of geometry could be explored in-depth. The transcripts of the interviews were thoroughly coded and categorised into the following significant themes: (1) Motivation and Interest in Learning Geometry, (2) Pre-requisite Knowledge about Geometry concepts, (3) Experiences and Familiarity with GeoGebra, and (4) Influence of GeoGebra Modelling on students' understanding of Geometry. Some of the participants' comments are included as representative samples to illustrate and support the themes.

8.1. Theme 1: Motivation and Interest in Learning Geometry

One of the common trends revealed in the interviews was that the motivation and interest of students in learning Geometry was improved after the implementation of the GeoGebra Modelling Approach. The participants always stated that the interactive aspect of GeoGebra made the geometry lessons more enjoyable, engaging and learner centered. This opportunity to "play" with geometric shapes and to get immediate feedback on the visual results boosted their enthusiasm for learning and raised their confidence and positive perceptions in solving geometric problems.

8.1.1. Group One Explained

"Learning was fun and engaging because of the easy nature of learning with the tool; the instant visual feedback helped us to understand Geometry better than before." (Participant 1)

Another group, said that GeoGebra was made interactive and this added to the enjoyment of the lessons as the students could see the results of the geometric constructions right away, thus making them more confident and interested in the learning process.

From the responses, worth noting that the GeoGebra Modelling Approach has made a positive effect on students' motivation and engagement in learning Geometry. The results are consistent with those of (Jelatu et al., 2018; Seloraji & Eu., 2017) which showed that GeoGebra provides dynamic visualisation and an interactive learning environment that increases students' interest and engagement.

8.2. Theme 2: Pre-requisite Knowledge of Geometry Concepts

Another theme of interest in the context of the study was students' understanding of Geometry before the introduction of the GeoGebra Modelling Approach. Most of the participants stated that they had had little or no prior experience in learning.

The participants mentioned that their earlier learning experiences were mainly theoretical, relying on memorisation of formulas and definitions. They were able to remember mathematical procedures but had problems visualising geometric figures and understanding abstract concepts like spatial relationships and properties of angles.

8. 2. 1. Group Three Explained

"We usually just had to learn the formulas and definitions and had no idea what they would look like or how they worked." (Participant 3)

Other groups also reported that conventional lessons did not offer enough opportunities to visualise, which posed a challenge to understanding Geometry. These responses indicate that the conventional teaching methods foster procedural rather than conceptual understanding of Geometry.

8. 3. Theme 3: Experience and Familiarity with GeoGebra

The interviews also showed that none of the participants had any previous experience with GeoGebra before the intervention. Although they were initially unfamiliar with the software, students reported that this software was easy to use and helped to improve their recognition, construction and analysis of geometric figures.

8. 3. 1. Group Four Stated

"It was my first time using GeoGebra, and I found it to be easier to use for Geometry, as I could see and play with the shapes." (Participant 4)

The participants also explained how GeoGebra helped to visualise geometric concepts and offered a learning experience that was very different from the way they were used to learning on the whiteboard. The results from this study indicate that the implementation of GeoGebra had a significant effect on the students' learning process, providing an opportunity for visualisation, conceptual understanding, and cognitive involvement in their learning.

8. 4. Theme 4: Influence of GeoGebra Modelling on Students' Understanding of Geometry

The most thorough theme that arose from the interviews was the influence of the GeoGebra Modelling Approach on students' knowledge of Geometry. Participants regularly expressed that the software made conceptual learning more tangible and enabled dynamic manipulation and visualisation of 3D geometric figures, thus creating more concrete learning experiences.

8. 4. 1. Group Two Explained

GeoGebra was useful as *"I could move the figures and see what is going on, and I understood Geometry."* (Participant 2)

Participants also noted that GeoGebra enhanced the development of reasoning and problem-solving skills, as they could experiment with various solution strategies, check their own work and get visual feedback. They also claimed that the software helped them develop their spatial thinking and helped them make meaningful links between the concepts of Geometry and the practical applications in their daily lives. In addition, the use of two-dimensional and three-dimensional modelling encouraged independent learning, accuracy in solving Geometry problems and moved students from memorisation-based learning to conceptualisation.

In general, these responses show that GeoGebra facilitated meaningful learning by providing visualisation, exploration, development of critical thinking, and conceptual understanding of Geometry.

The qualitative results show that a positive perception has emerged, and that it has become overwhelming for the students in the sense that the school-based learning environment has been recreated. In every theme, the participants regularly referred to GeoGebra as a fun and efficient teaching tool that increased their motivation, conceptual understanding, visualisation skills, confidence and problem-solving skills. Students also wrote that the software had a dynamic and interactive element that motivated students to participate actively in the learning process, explore the material on their own, and have a better understanding of geometric concepts, which helps to overcome many of the problems of the conventional teacher-centered methods.

The overall results of the interview indicate that the GeoGebra Modelling Approach is pedagogically significant when teaching Geometry in TVET institutions. The approach not only had a positive perception of students' thinking in terms of geometric concepts, but it also had a positive effect on key affective outcomes, such as motivation, engagement, confidence and learner autonomy. The qualitative results of the study support the quantitative results and further confirm that the GeoGebra Modelling Approach is an effective instructional approach to improve students' learning experiences and academic achievement in Geometry.

The qualitative results of the interviews complemented the quantitative results. After exposure to the GeoGebra Modelling Approach, participants always mentioned that their motivation to learn increased, their understanding of the concepts improved, their visualisation skills got better, their confidence to solve geometry problems increased, and their problem-solving skills were enhanced. Students also pointed out that GeoGebra was interactive and learner-centered, and they found it easier to investigate geometric concepts using it than in their classroom.

Results showed that the TVET students' perceptions of the use of GeoGebra were very positive in learning geometry with the modelling approach. Students found GeoGebra to be an interesting, interactive and effective learning tool that contributed to their learning and enjoyment of geometry.

9. Discussion

The literature reviewed shows that the use of technology, specifically GeoGebra in the teaching of Geometry can greatly improve the learning outcomes of Technical and Vocational Education and Training institutions. The theoretical, empirical and contextual aspects of the GeoGebra Modelling Approach are summarised in the discussion below to explain how the GeoGebra Modelling Approach is an innovative instructional approach that can impact mathematics instruction in Ghana's TVET sector.

9.1. Geometry and Digital Modelling Integration

Until now, geometry was taught in a teacher-centered way, focusing on rules and formulas to be memorised. These systematic procedures, however, do not always foster conceptual understanding and spatial reasoning (Tay & Wonkyi, 2018; Ubi & Odiong, 2018). The reviewed studies showed that technology-based interventions, in particular through the use of dynamic mathematics software, enable learners to visualise relationships between Geometric objects, manipulate the objects in real time, and make abstract mathematics concepts more concrete and real (Arbain & Shukor, 2015; Bhagat & Chang, 2015). It is an integration that can be applied within TVET contexts and is able to fill a gap between the theory and practical application of mathematics, in order to make the instruction of Geometry more meaningful in vocational education.

9.2. The GeoGebra Pedagogical Value

GeoGebra has become one of the most effective digital tools to be used in mathematics education (Narh-Kert & Sabtiwu, 2022). It has the ability to connect algebraic, graphical and numerical representations, leading to a rich understanding of concepts. Research conducted by (Jelatu et al., 2018; Seloraji & Eu, 2017) show that students who learned by using GeoGebra perform better than those who learned from conventional methods. The findings are in support of constructivism and cognitive learning theories that suggest that learning is an active process rather than a passive one. GeoGebra is geared toward exploration and experimentation, allowing students to test out their predictions, get instant feedback, and correct their errors. This interaction helps to turn the classroom into a collaborative learning area, rather than a learning area dominated by the teacher.

9.3. The Technical and Pedagogical Skills of Teachers

The literature highlights that teachers' Technological Pedagogical Content Knowledge (TPCK) has been identified as one of the key factors to the effectiveness of GeoGebra (Verhoef et al., 2015). Implementing digital tools into teaching requires both pedagogical and technological expertise, which teachers need to acquire the understanding of Geometric concepts. However, the level of teacher preparedness in Ghana is not uniform because of limited opportunities for professional development, low level of digital infrastructure, and reluctance to innovation (Brown-Joseph, 2010). To fully realise the potential effect of GeoGebra in TVET classrooms, continuous capacity building and institutional support are needed to help teachers achieve this direction.

9.4. Theoretical and Conceptual Reflections

In terms of theory, the GeoGebra Modelling Approach can be said to be in line with Mathematical Modelling Theory (Blomhøj & Jensen, 2003; Maaß, 2006) and Constructivist Learning Theory (Piaget, 1970). The process of mathematical modelling is one that involves the learner representing a problem in the real world as a mathematical model, solving it and then explaining the solution in the real world processes that GeoGebra can easily assist with by visualising the mathematics dynamically. The constructivist approach to learning, on the other hand, treats learning as an active process of meaning-making, and this approach is operationalised in GeoGebra by constructing and reconstructing Geometric models interactively. The complementarity of these frameworks gives a strong argument to use GeoGebra in teaching geometry, especially when students are required to relate theory to applications using technical skills.

10. Conclusion

The results of this study reflect the effectiveness of the GeoGebra Modelling Approach in improving students' learning outcomes in Geometry. The study has led to the following conclusion: The students who were exposed to GeoGebra showed significantly higher achievement levels than the students in conventional classrooms. The instructiveness, visual and modelling features of GeoGebra help to foster conceptual understanding and problem solving in Geometry. The results of interaction between groups and pretest scores showed that GeoGebra was suitable for all students regardless of their ability, and it was a learning approach that met all students' learning needs. The students' learning outcomes showed high observed power (98%) and large effect size (partial $\eta^2 = .312$), thus providing a meaningful and practically significant effect of GeoGebra intervention, which has pedagogical value. They are consistent with the Cognitive Load theory, as it states that the use of digital visualisation and dynamic manipulation of geometric concepts decreases cognitive load and enhances the construction of knowledge.

In conclusion, the research shows that the use of GeoGebra as a Modelling approach in teaching and learning geometry has a positive effect on the students' understanding, memory retention, and motivation of learning mathematics, providing a lasting solution to improve students' mathematics learning outcomes in TVET institutions.

11. Implications for TVET Education

The study reveals that the application of GeoGebra significantly increases achievement at all ability levels, spatial reasoning and motivation of the TVET students. The modelling method helps students to learn how to analyse technical drawings, understand construction drawings, and solve measurement-related issues with higher accuracy. These skills are directly

applicable to other disciplines like carpentry, engineering and architecture. Moreover, GeoGebra is accessible and open-source, which makes it a low-cost tool in resource-limited educational environments. GeoGebra allows students to practice and get instant feedback in an iterative way, so that students can be competent at the basic topics before moving on to advanced topics.

11.1. Limitations of the Study

The study was conducted in TVET institutions only; each institution had a minimum of 20 students due to the practical nature of the education offered. To arrive at the interview data these twenty students were further grouped into four groups of five. Self-report and potential selection bias were also used in the interviews and were carefully considered to minimize contamination of data.

11.2. Recommendations

The following recommendations are proposed for practice and policy, and for further research, based on the findings and conclusion:

11.2.1. Use of Technology in the Classroom

The GeoGebra Modelling Approach should be used for enhancing conceptual understanding and problem-solving ability for geometry in TVET mathematics teachers.

11.2.2. Professional Development

Organising continuous professional development (CPD) programmes that will increase teachers' competence in using technological products in teaching, especially GeoGebra.

11.2.3. Curriculum Enrichment

The Ghana Education Service (GES) and TVET curriculum developers must incorporate technology-based learning tools, such as GeoGebra, into the geometry syllabus to encourage the use of modelling, visualisation and real life applications.

11.2.4. Infrastructure and ICT Support

School administrators and policymakers should prioritise funding for the implementation of technology-enhanced instruction, including technology infrastructure such as computer(s), projectors and stable internet connectivity.

11.2.5. Monitoring and Evaluation

Education authorities should ensure mechanisms have been implemented to measure the effectiveness of any digital learning intervention to improve students' achievement in mathematics.

12. Recommendations for Further Research

Further studies should investigate context-specific approaches to maintaining the use of GeoGebra modelling and how it impacts learning outcomes in the long-term. As a corollary of this study, we recommend carrying out a longitudinal study, which aims to find out the attitude of TVET students in learning GeoGebra modelling-based pedagogy in Geometry.

Conflict of Interests Statement

The authors have no competing conflicts to declare that are relevant to the content of this article.

Authors Contributions

All authors contributed to the study conception and design. Dr. H.I. Bukari and Mr. K. Aninganigu performed materials preparation, data collection, first draft, writing and analysis. The methodology was written and the first draft reviewed by Dr. A.A. Alagbela and Dr. C.K. Sie. The final draft was edited by Prof. C.S. Bornaa and Prof. R. Govender and all authors commented on the previous version of the manuscript. All authors read and approved the final manuscript.

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