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The Effect of GeoGebra-Based Instruction on Students' Conceptual Understanding of Exponential Functions

Amalia Rasikhah Earliand[1*], Alfisyahra Alfisyahra[1], Muh Hasbi[1], Dasa Ismaimuzaa[1]

[1] Universitas Tadulako, Indonesia

**Email Correspondence:* amaliarskh@gmail.com

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ABSTRACT

Exponential functions pose conceptual challenges for secondary students due to their abstract nature. This quasi-experimental study investigated the effect of GeoGebra-based instruction on Grade 10 students' conceptual understanding in two Indonesian senior high schools (N = 132). A validated four-item essay test (r > 0.219; Cronbach's Alpha = 0.71) was administered before and after instruction. Mann–Whitney U analysis showed a significant difference in posttest conceptual understanding between the GeoGebra and conventional groups ($p < .001$), with a moderate-to-large effect size (r = 0.44). These results provide classroom-based empirical evidence that dynamic visualization through GeoGebra strengthens students' conceptual understanding and supports its structured integration in conceptually demanding mathematics topics.

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1. Introduction

Exponential functions are a core component of the senior high school mathematics curriculum due to their wide-ranging applications in fields such as biology, economics, and computer science. Despite their relevance, students often struggle to understand exponential functions, particularly in interpreting rapid exponential growth and the shapes of graphs that represent such phenomena(Cardozo & Possamai, 2019)(Nunes et al., 2017). These difficulties are frequently attributed to students' tendency to focus on procedural mastery rather than conceptual understanding, thereby hindering their ability to relate exponential models to real-

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world contexts(Dorner & Ableitinger, 2022)(Hidayat et al., 2023)(Liburd & Jen, 2021).

Compounding these challenges is students' limited ability to visualize and interpret exponential graphs. Transitions from linear to exponential thinking require more sophisticated conceptual frameworks, which traditional instructional approaches often fail to adequately support(Iparraguirre-Villanueva et al., 2024) (Nunes et al., 2017). In Palu City, similar issues were observed at State Senior High School 2 Palu and State Senior High School 4 Palu. Based on preliminary classroom observations and informal discussions with mathematics teachers, the integration of digital technology—particularly dynamic mathematics software—into the teaching of exponential functions remained limited. GeoGebra, a dynamic mathematics software, had not yet been employed to facilitate student visualization or understanding of exponential growth patterns(Putra et al., 2021)(Weinhandl et al., 2020).

GeoGebra provides an avenue to enhance students' understanding of abstract mathematical concepts through the value of interactive, student-centered, and multi-representational learning environments. This approach is rooted in constructivist and mathematical representation theories. These theoretical underpinnings align well with GeoGebra's capabilities and its pedagogical application.

A growing body of research underscores GeoGebra's potential to support students' conceptual understanding through dynamic and interactive visual representations. By enabling real-time manipulation of mathematical objects, the software facilitates the coordination of graphical and algebraic representations, thereby strengthening representational fluency and deep structural comprehension(Aliyu et al., 2021)(Daulay et al., 2021)(Solvang & Haglund, 2021)(Wassie & Zergaw, 2019)(Zagoto et al., 2025). Within a constructivist framework, such interactive environments position learners as active meaning-makers, allowing conceptual understanding to emerge through exploration rather than procedural imitation. Increased motivation and participation reported in prior studies(Wahyuni et al., 2025) can thus be interpreted as consequential to, rather than independent from, deeper conceptual engagement.

Despite these documented affordances, the effectiveness of GeoGebra remains context-sensitive. Variations in instructional design, teacher expertise, and technological infrastructure contribute to inconsistent empirical outcomes(Albaladejo et al., 2015)(Dildabayeva & Zhaydakbayeva, 2024). More importantly, although GeoGebra has been extensively examined in geometry and general algebra contexts, rigorous quasi-experimental evidence specifically addressing its effect on students' conceptual understanding of exponential functions in authentic classroom settings remains limited(Abar & Alencar, 2013)(Nunes et al., 2017).

This gap is particularly significant given the abstract and dynamic nature of exponential functions, which demand coordinated interpretation across multiple representations. Accordingly, there is a need for classroom-based quasi-experimental research that systematically investigates how GeoGebra-based instruction influences high school students' conceptual understanding within real instructional contexts(Dorner & Ableitinger, 2022)(Liburd & Jen, 2021)(Putra et al., 2021). Responding to this need, the present study examines the effect of GeoGebra-based instruction on Grade 10 students' conceptual understanding of exponential

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functions in two Indonesian senior high schools. By employing a quasi-experimental design situated in authentic classroom practice, this research contributes empirically grounded evidence to the discourse on technology-enhanced mathematics instruction and offers contextually situated insights for pedagogical development(Albaladejo et al., 2015)(Hidayat et al., 2023).

2. Method

2.1. Research Design

This study employed a quantitative quasi-experimental design using a nonequivalent control group structure. Two intact classes were assigned as the experimental and control groups. The experimental group received GeoGebra-based instruction, whereas the control group was taught through conventional direct instruction. Students' conceptual understanding of exponential functions was measured using a pretest and posttest administered to both groups. The pretest established baseline comparability, and the posttest assessed the effect of the instructional intervention. This design is appropriate for classroom-based research where random assignment is not feasible, while still allowing systematic comparison between instructional approaches(Seloane et al., 2023)(Yimer & Feza, 2019).

Table 1. Nonequivalent Control Group Design

Group	Pretest (O_1)	Instructional Treatment	Posttest (O_2)
Experimental	O_1	X (GeoGebra-Based Instruction)	O_1
Control	O_2	Conventional Direct Instruction	O_2

Definition,

O_1 = Pretest measuring students' conceptual understanding of exponential functions

X = GeoGebra-based instructional intervention

O_2 = Posttest measuring students' conceptual understanding of exponential functions

2.2. Participants and Data Sources

The study was conducted in two public senior high schools: State Senior High School 2 Palu (*SMA Negeri* 2 *Palu*) and State Senior High School 4 Palu (*SMA Negeri* 4 *Palu*). A total of 132 tenth-grade students were selected through purposive sampling, which included 66 students in the experimental group and 66 in the control group. This technique was used to ensure group homogeneity based on recommendations from mathematics teachers regarding curriculum exposure and instructional settings. The primary data source consisted of students' scores on a validated test measuring conceptual understanding of exponential functions, administered before and after the instructional intervention.

2.3. Research Procedure

The research procedure consisted of structured phases to ensure methodological rigor. During the planning stage, lesson plans were developed for both instructional conditions, GeoGebra-based materials were prepared, and a test measuring students' conceptual understanding of exponential functions was constructed in alignment with the national curriculum. The instrument underwent expert review to establish content validity, followed by empirical testing to

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determine reliability, item difficulty, and discrimination indices.

To control for potential teacher effects, the same mathematics teacher taught both the experimental and control groups. The teacher had prior instructional experience and received preparatory training in implementing GeoGebra-based instruction to ensure consistency and fidelity of treatment across sessions. Following instrument validation, a pretest was administered to both groups to establish baseline comparability in conceptual understanding.

The experimental group then received GeoGebra-based instruction across three 45-minute sessions emphasizing dynamic visualization and multiple representations of exponential functions, whereas the control group received conventional direct instruction covering the same content. After the intervention, a posttest—equivalent in structure and content to the pretest—was administered to measure students' conceptual understanding. Data were subsequently analyzed using descriptive and inferential statistical procedures(Yimer & Feza, 2019).

2.4. Instrumentation and Feasibility Analysis

The primary instrument was a validated test consisting of four essay items designed to assess students' conceptual understanding of exponential functions in alignment with the curriculum's cognitive objectives. Validity was tested using Pearson correlation, and internal consistency was measured via Cronbach's Alpha. Difficulty and discrimination indices were also examined to ensure quality. Table 2 demonstrated an overall reliability (Cronbach's alpha) of 0.71, while the item performance was assessed using Corrected Item-Total Correlation (CITC).

Table 2. Instrument Quality Analysis

Item	r-calculated	r-table	Validity	Mean	Max Score	Difficulty Index	Category	CITC	Discri-mination
1.	0.831	0.219	Valid	17.62	25	0.705	Easy	0.566	Good
2.	0.775	0.219	Valid	21.57	25	0.863	Easy	0.591	Good
3.	0.695	0.219	Valid	22.41	30	0.747	Easy	0.444	Good
4.	0.642	0.219	Valid	7.47	20	0.374	Moderate	0.472	Good

2.5. Data Analysis Techniques

Data analysis was conducted using SPSS software. Descriptive statistics provided summary metrics such as mean and standard deviation. The Kolmogorov–Smirnov test was used to check data normality. Since posttest scores from the control group were not normally distributed ($p < .05$), the Mann–Whitney U test was used to compare the two independent groups (Febrianti & Dasari, 2024)(Uwurukundo et al., 2022). This test is appropriate for non-normal, ordinal, or outlier-prone data. The hypotheses tested were as follows:

a. H_0: There is no significant difference in students' conceptual understanding of exponential functions between those taught using GeoGebra-based instruction and those taught using conventional direct instruction.
b. H_1: There is a significant difference in students' conceptual understanding of exponential functions between those taught using GeoGebra-based instruction and those taught using conventional direct instruction.

2.6. Ethical Considerations

The study adhered to academic ethical standards. Informed consent was obtained from the schools and students involved. Confidentiality of participants' data was

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assured, and the intervention posed no risks or undue burden. Instructional activities were aligned with the national curriculum, and equity was maintained across groups. No participant was disadvantaged in the learning process (Mataheru et al., 2023)(Muslim et al., 2023).

3. Results and Discussion

3.1. Overview of Research Implementation

The implementation of the research proceeded as planned, involving active participation from both teachers and students at the two selected senior high schools. Student attendance remained consistently stable throughout the instructional sessions, and no significant technical or administrative issues were encountered. In the experimental group, the integration of GeoGebra stimulated high student engagement, as evidenced by their enthusiasm in exploring the software's features and their active involvement in classroom discussions. Teachers also reported that the media was helpful in visually and dynamically illustrating the concepts of exponential functions.

Table 3. Descriptive Statistics of Pretest and Posttest Scores

Group	N	Pretest Min	Pretest Max	Pretest Mean	Posttest Min	Posttest Max	Posttest Mean
Control	66	36	77	57.41	54	89	81.00
Experimental	66	23	88	60.74	84	93	87.97

In contrast, instruction in the control group was delivered using conventional methods, relying primarily on verbal explanations and written exercises. Although the lessons ran smoothly, the classroom interaction was predominantly one-directional. Assessment for both groups was conducted simultaneously using a pretest and posttest, administered with identical content and within the same time frame to ensure fairness across conditions. Table 3 shows that both groups demonstrated comparable baseline conceptual understanding, as reflected in their pretest means. Following the intervention, the experimental group exhibited a higher posttest mean compared to the control group, indicating a stronger improvement in students' conceptual understanding of exponential functions.

3.2. Statistical Analysis and Interpretation

To ensure the validity of the statistical analysis, it was essential to verify that the data met the required parametric assumptions. Prior to hypothesis testing, normality was examined using the Kolmogorov–Smirnov test. The results are presented in Table 4.

Table 4. Normality Test Results

Data	Sig.
Pretest (Control)	$< .001$
Posttest (Control)	$< .001$
Pretest (Experimental)	$.200$
Posttest (Experimental)	$.063$

Table 4 indicates that the control group data were not normally distributed ($p < .05$). The experimental group satisfied the normality assumption. Accordingly, the non-parametric Mann–Whitney U test was used to compare

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posttest scores between groups.

Table 5. Mann–Whitney U Test Ranks

Group	N	Mean Rank	Sum of Ranks
Experimental	66	83.23	5493.50
Control	66	49.77	3284.50

The higher mean rank of the experimental group suggests stronger post-intervention conceptual understanding compared to the control group. The results in Tables 5 and 6 indicate a statistically significant difference between the experimental and control groups ($p < .001$). The elevated mean rank of the experimental group indicates that the utilization of GeoGebra substantially enhanced students' ability in mastering exponential functions.

Tabel 6. Summary of Mann–Whitney U Test Statistics

Statistic	Value
Mann–Whitney U	1073.50
Wilcoxon W	3284.50
Z	-5.06
p-value (2-tailed)	$< .001$

The Mann–Whitney U test revealed a statistically significant difference in posttest conceptual understanding between the experimental and control groups ($p < .001$). Therefore, the null hypothesis was rejected, indicating that GeoGebra-based instruction produced significantly different outcomes compared to conventional direct instruction. Descriptive statistics further show that the experimental group achieved higher posttest scores, suggesting stronger conceptual understanding of exponential functions following the intervention.

To examine the practical significance of the findings, the effect size (r) was calculated using the formula $r = Z/\sqrt{N}$, where Z represents the standardized test statistic and N refers to the total number of observations across both groups. For non-parametric tests such as the Mann–Whitney U, the total sample size ($N = 132$) is conventionally used in the denominator to estimate effect magnitude (Field, 2018)(Pallant, 2020). With $Z = -5.06$ and $N = 132$, the calculated effect size was,

$$r = \frac{5.06}{\sqrt{132}} \approx 0.44$$

According to commonly accepted benchmarks(Cohen, 1988), this value represents a moderate to large effect, indicating that GeoGebra-based instruction had a practically meaningful impact on students' conceptual understanding of exponential functions, beyond statistical significance. The findings indicate that GeoGebra-based instruction had a moderate-to-large effect ($r = 0.44$) on students' conceptual understanding of exponential functions. Beyond statistical significance, this magnitude suggests meaningful pedagogical impact within authentic classroom settings.

In educational research, effect sizes of this scale are considered substantial, particularly in quasi-experimental designs conducted under natural instructional constraints(Cohen, 1988). The observed effect may be attributed to several

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interrelated cognitive mechanisms activated through dynamic visualization and representational coordination. From a constructivist perspective, GeoGebra facilitates active knowledge construction by enabling students to manipulate parameters and immediately observe changes in graphical representations(Anwar et al., 2025)(Seloane et al., 2025). Such real-time feedback reduces cognitive load associated with abstract symbol manipulation and supports the integration of visual-spatial and symbolic processing. In the context of exponential functions where growth patterns are non-linear and often counterintuitive dynamic visualization helps students internalize structural relationships rather than rely solely on procedural computation.

Drawing on mathematical representation theory, the effect size can also be interpreted as a consequence of strengthened representational fluency. GeoGebra allows simultaneous coordination of algebraic expressions, graphical curves, and numerical tables, fostering deeper structural connections(Mensah & Nabie, 2021)(Safrida et al., 2020). This coordinated multi-representational engagement likely enhanced students' conceptual understanding by clarifying the relationship between exponential parameters and graphical behavior.

Compared with prior research, the observed effect size ($r = 0.44$) lies at the upper range of the moderate category commonly reported in GeoGebra-based interventions(Putra et al., 2021)(Wahyuni et al., 2025). While many studies document small-to-moderate improvements in conceptual understanding, the magnitude found here suggests a comparatively stronger impact within a classroom-based quasi-experimental context. Differences in reported effect sizes may reflect variation in topic specificity, intervention intensity, teacher expertise, and technological readiness(Albaladejo et al., 2015)(Dildabayeva & Zhaydakbayeva, 2024). Given the abstract and non-linear nature of exponential functions, the relatively stronger effect may indicate that dynamic visualization plays a particularly decisive role in supporting conceptual restructuring and reducing misconceptions in this domain(Canonigo, 2024).

Practically, these findings support the structured integration of GeoGebra in teaching conceptually demanding topics at the secondary level. The results provide classroom-based quasi-experimental evidence that dynamic mathematical software can meaningfully strengthen students' conceptual understanding when implemented with instructional fidelity. While the contextualized design enhances ecological validity, the generalizability of the findings remains contingent upon comparable instructional conditions, teacher preparedness, and technological infrastructure(Kul, 2018)(Zagoto et al., 2025)(Zainudin et al., 2025).

Accordingly, several limitations should be acknowledged. The sample was geographically restricted, the design relied exclusively on quantitative measures, and long-term retention of conceptual understanding was not examined. Future research should adopt longitudinal and mixed-method approaches to investigate sustained conceptual development and to determine how varying instructional designs optimize the cognitive affordances of dynamic technology across diverse mathematical domains and student populations.

4. Conclusions

This study demonstrates that GeoGebra-based instruction exerts a statistically significant and practically meaningful effect on students' conceptual understanding of exponential functions. Consistent with the proposed hypothesis,

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a statistically significant difference in conceptual understanding was identified between students who received GeoGebra-based instruction and those who received conventional direct instruction, leading to the rejection of the null hypothesis. The moderate-to-large effect size ($r = 0.44$) indicates that the observed gains extend beyond statistical significance and reflect substantive instructional impact within authentic classroom contexts. The findings reinforce the theoretical proposition that dynamic visualization and coordinated multiple representations facilitate conceptual restructuring in abstract mathematical domains. When implemented with instructional fidelity, GeoGebra supports deeper structural understanding rather than procedural replication, particularly for non-linear concepts such as exponential growth.

Importantly, this research provides empirical quasi-experimental evidence derived directly from authentic classroom implementation in the Indonesian secondary education context, addressing a documented gap concerning rigorous investigations of students' conceptual understanding of exponential functions. As such, the practical implication is grounded not in theoretical projection but in observed instructional practice: structured and fidelity-based integration of GeoGebra can be adopted in comparable classroom settings to strengthen conceptual understanding in conceptually demanding mathematical domains. While generalization should remain context-sensitive, the classroom-based nature of the evidence enhances its pedagogical relevance and applicability. Future studies should extend this line of inquiry by examining long-term retention, diverse learner populations, and variations in instructional design to further clarify the mechanisms through which technology-enhanced environments strengthen conceptual understanding.

Author Contributions

For transparency, we encourage authors to submit an author statement file outlining their individual contributions to the article using the relevant CRediT roles: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Roles/Writing - original draft; Writing - review & editing. Authorship statements should be formatted with the names of authors first and CRediT role(s) following.

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Declaration of Competing Interest

Authors must state any potential competing interests that may affect or prejudice their study, such as financial or personal ties, rivalries, or religious convictions. Example of these competing interests include monetary relationships or agreements with an establishment whose invention was utilized or mentioned in the research; any monetary interests derived from a business relationship with a competitor; any remuneration made directly to an author(s) to write the manuscript; and other monetary connections, or other circumstances that may elevate questions about the objectivity of the work or the views expressed within

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the text. Authors may be requested for more information on the nature of the stated interests. The article may be withheld from publishing depending on the specifics of the case. If the manuscript is accepted for publication, the competing interests are disclosed in a note before the references section.

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