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Enhancing Conceptual Understanding of Real Variable Functions in Engineering Students Through GeoGebra: A Quasi-Experimental Study

Abstract*– The integration of dynamic mathematical software has become increasingly relevant in engineering education, particularly in post-pandemic contexts that demand interactive and accessible learning environments. This study examines the effect of GeoGebra, an open-source dynamic mathematics platform, on the conceptual understanding of real variable functions among first-year engineering students in Peru. A quasi-experimental design with pre-test and post-test control groups was implemented (n = 40). Instrument reliability was confirmed through Cronbach's alpha (α = 0.87). Statistical analyses included Shapiro–Wilk normality testing, Levene's homogeneity test, independent samples t-test, and effect size estimation using Cohen's d. Results demonstrated statistically significant differences in post-test performance between the experimental group (M = 15.5, SD = 2.21) and the control group (M = 12.4, SD = 1.96), t(38) = 4.073, p = 0.001. The calculated effect size was large (Cohen's d = 1.48), indicating a substantial educational impact. Students exposed to GeoGebra achieved higher levels of conceptual and graphical comprehension compared to those receiving traditional instruction. These findings provide empirical evidence supporting the integration of dynamic open-source technologies to enhance mathematical abstraction and learning outcomes in engineering education.

***Keywords*-- GeoGebra; engineering education; real variable functions; conceptual understanding; quasi-experimental design; effect size.**

I. INTRODUCTION

Mathematics constitutes a foundational pillar in engineering education, particularly during the first years of undergraduate training, where the development of analytical reasoning and abstraction skills is essential. However, persistent difficulties in the comprehension of real variable functions continue to affect academic performance in higher education contexts. These challenges are often associated with gaps in prior knowledge, socioeconomic constraints, curriculum limitations, and deficiencies in foundational mathematical preparation [1], [2]. Such factors negatively impact students' progression in subsequent courses and their professional formation.

In the study of functions, conceptual misunderstandings frequently emerge in the identification of domain, range, and graphical representations [3]. Students often exhibit technical inaccuracies, distorted interpretations of theorems, unverified procedures, and incorrect reasoning processes [4]. Recurring errors in specific topics, such as logarithmic functions, further illustrate the cognitive complexity inherent in mathematical abstraction [5]. These issues highlight the necessity of adopting pedagogical strategies capable of supporting conceptual clarity and representational flexibility.

Information and Communication Technologies (ICT) have progressively become central to educational innovation in higher education [6], [7]. International educational frameworks emphasize that academic excellence depends not only on theoretical instruction but also on students' capacity to develop digital competencies and effectively utilize technological tools [8]. Within this context, dynamic mathematical environments offer opportunities to bridge the gap between symbolic manipulation and graphical interpretation, enhancing conceptual understanding and long-term retention [9], [10].

Empirical evidence supports the integration of dynamic software in the teaching of mathematical functions. Studies employing computer-supported collaborative learning (CSCL) approaches demonstrate superior learning outcomes compared to traditional instructional methods [11]–[14]. Furthermore, student motivation—an essential variable in mathematical achievement—is influenced by both internal and external factors, including instructional design and the learning environment [1], [15]–[19]. The use of multiple semiotic representations has proven particularly effective in diversifying cognitive access to mathematical concepts, thereby strengthening comprehension and engagement [10], [20].

The versatility of dynamic software extends across diverse mathematical domains, including geometry [21], [22], analytic geometry [24], linear functions [9], [25], polygons [26], calculus [27], and functions with parameters [13], [34]. Quasi-experimental and mixed-methods studies have reported significant improvements in students' performance when GeoGebra is incorporated into instructional practice, particularly in linear and quadratic functions [28], [29], exponential and logarithmic functions [12], [30], and trigonometry [31]–[33]. These findings suggest that dynamic visualization supports both conceptual and procedural learning processes.

GeoGebra, as an open-source dynamic mathematics platform, integrates symbolic computation and graphical visualization within a unified interactive environment [35]. Its accessibility across devices, cost-effectiveness, and strong user community position it as a viable alternative for institutions seeking equitable digital transformation in mathematics education.

Despite the growing body of evidence supporting dynamic mathematics software, empirical studies employing rigorous statistical validation, effect size analysis, and theoretically grounded instructional design remain limited in Latin American engineering contexts. Moreover, many studies report positive effects of GeoGebra without explicitly describing the pedagogical structure of the intervention, the criteria used to select the mathematical functions, or the way in which symbolic and graphical representations are systematically articulated. Therefore, there is a need to examine not only the magnitude of GeoGebra's instructional impact, but also the pedagogical mechanisms through which dynamic software supports conceptual understanding of real variable functions during the first semester of engineering programs.

Accordingly, this study examines the influence of GeoGebra-supported instruction on the conceptual understanding of real variable functions among first-year engineering students at the Universidad Nacional de Juliaca, Peru. Through a quasi-experimental design incorporating statistical validation and effect size estimation, the research evaluates both the significance and magnitude of instructional impact, thereby addressing the limited quantitative evidence available in Latin American engineering education contexts.

II. METHODOLOGY

A. Research Design

This study employed a quasi-experimental design with pre-test and post-test control groups, following the framework proposed by Campbell and Stanley [36]. Although participants belonged to intact classroom groups and full randomization was not feasible due to institutional constraints, equivalence between groups was statistically verified through pre-test comparison. The design structure is presented in Table 1.

Table 1.
DATA TREATMENT

Groups	pre-test	Treatment	Post test
Experimental Group (EG)	O1	X	O2
Control Group (CG)	O1	-	O2

Note: Adapted from Campbell and Stanley (1995)

O_1 denotes the pre-test evaluation, X represents the instructional intervention using GeoGebra, and O_2 corresponds to the post-test evaluation.

B. Participants and Sampling

The sample consisted of 40 first-semester students enrolled in a basic mathematics course within engineering programs. Participants were selected from a population of approximately 300 students through purposive non-probability sampling, as described by Hernández-Sampieri and Mendoza [37].

The sample was divided into an experimental group ($n = 20$) and a control group ($n = 20$).

This sampling approach ensured homogeneity in academic level and curricular exposure. Pre-test statistical analysis confirmed no significant differences between groups ($p > 0.05$), supporting baseline equivalence.

C. Instrument Design, Validation, and Reliability

Data were collected through structured pre-test and post-test assessments composed of 20 items designed to evaluate both conceptual and graphical understanding of real variable functions.

The instrument included:

- Closed polytomous items assessing conceptual knowledge.
- Open-ended questions evaluating graphical interpretation and representational skills.

The validation process included:

- Content validation by three experts in mathematics education.
- Reliability analysis using Cronbach's alpha ($\alpha = 0.87$), indicating high internal consistency.

Item discrimination and difficulty analysis to ensure psychometric adequacy.
Knowledge levels were classified according to institutional grading criteria, as shown in Table 2.

Table 2.
EVALUATION SCALE

Grade Range	Level	Description
0–10	Fail	Insufficient knowledge
11–13	Sufficient	Elementary knowledge
14–16	Good	Knowledge with notable errors
17–18	Very Good	Knowledge with minor errors
19–20	Excellent	High-level knowledge

Note: Adapted from Universidad Nacional Mayor de San Marcos (2021) and Universidad Ricardo Palma (s.f.).

D. Intervention Procedure

The intervention was conducted over a six-week period and consisted of ten sessions of two hours each, corresponding to the second instructional unit of the mathematics course. The instructional content was structured following the theoretical approaches of Apostol [38] and Gel'fand et al. [39], ensuring a progressive development of the concept of real variable functions.

The sequence of topics was organized to reflect increasing levels of mathematical complexity and conceptual abstraction. It included real functions of a real variable and special functions; quadratic functions; absolute value and square root functions; unit step, sign, and floor functions; piecewise and power functions; properties such as increasing/decreasing behavior and even/odd symmetry; exponential and logarithmic functions; trigonometric functions; and inverse trigonometric functions.

The instructional design of the intervention was grounded in the theory of semiotic representation registers proposed by Duval (2006), which emphasizes the coordination between algebraic and graphical representations as a fundamental condition for conceptual understanding in mathematics. Within this framework, GeoGebra was integrated as a mediating tool to support the dynamic transformation between symbolic expressions and their graphical representations.

In the experimental group, GeoGebra was systematically employed to facilitate dynamic visualization, parameter manipulation, and graphical modeling of real variable functions. Learning activities were designed to promote exploration of functional behavior through real-time interaction, enabling students to observe how algebraic changes affect graphical representations. This approach was complemented by guided discovery and collaborative problem-solving strategies, fostering active learning and enhancing representational fluency.

Furthermore, the selection of functions responded to both mathematical and pedagogical criteria. From a mathematical perspective, functions were chosen to represent diverse functional families and transformations. From a pedagogical standpoint, emphasis was placed on functions that allow clear articulation between symbolic and graphical registers, particularly those involving parameter variation, transformations, and domain–range analysis.

The intervention also followed a guided discovery learning approach aligned with constructivist principles, where students actively engaged in hypothesis formulation, parameter manipulation, and validation of results through visualization. This design promoted deeper conceptual understanding through active cognitive engagement and iterative reasoning processes.

In contrast, the control group received traditional instruction based on lecture-centered explanations, static board representations, and individual and group exercises without the use of dynamic visualization tools.

Pre-test and post-test assessments were administered under standardized conditions, with a duration of 40 minutes each.

E. Statistical Analysis

Statistical analysis was conducted to evaluate group equivalence and determine the impact of the instructional intervention. Data distribution was first examined using the Shapiro–Wilk test to assess normality assumptions, followed by Levene's test to verify homogeneity of variances between groups. Given that parametric assumptions were satisfied, differences in post-test performance were analyzed using an independent samples t-test. Additionally, the magnitude of the instructional effect was estimated through Cohen's d to quantify practical significance beyond statistical significance. The level of significance was established at $\alpha = 0.05$. Effect size magnitude was interpreted according to conventional criteria, where values of 0.20 indicate a small effect, 0.50 a medium effect, and values equal to or greater than 0.80 represent a large effect.

Confidence intervals for the mean difference were also calculated to enhance interpretability of the results.

III. RESULTS

The comparative results between the experimental and control groups are presented in Figures 1 and 2, as well as in Tables 4 and 5.

A. Descriptive Analysis

As illustrated in Figure 1, pre-test scores for both groups were notably low, with mean values of 2.25 (experimental group) and 2.15 (control group), indicating insufficient prior knowledge of real variable functions. No statistically significant differences were observed at baseline ($p > 0.05$), confirming initial group equivalence.

Following the six-week instructional intervention, post-test results revealed a substantial improvement in both groups; however, gains were markedly higher in the experimental group. Students exposed to GeoGebra achieved a mean score of 15.5 (SD = 2.21), corresponding to a "good" performance level according to the institutional grading scale. In contrast, the control group obtained a mean score of 12.4 (SD = 1.96), categorized as "sufficient."

Notably, 100% of students in the experimental group scored 12 or higher, whereas only 50% of students in the control group reached this threshold. Score dispersion ranged from 12 to 18 in the experimental group and from 10 to 16 in the control group, as shown in Figure 1.

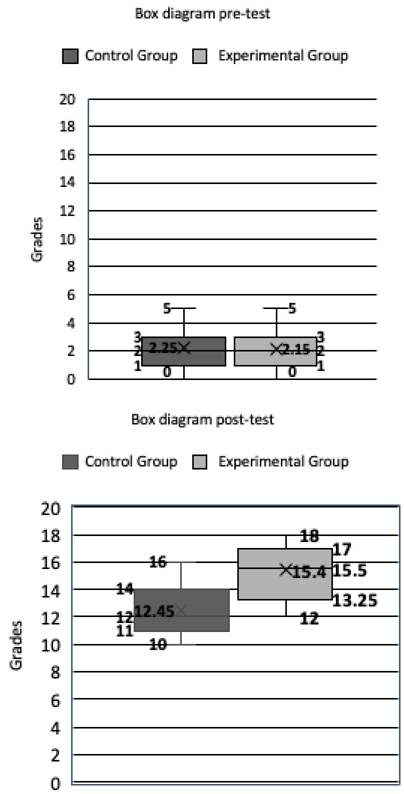

Figure 1. Box plot diagram pretest and post-test.

B. Distribution of Performance Levels

Figure 2 presents the distribution of students across performance categories. In the control group, most students were classified within the "good" level, with a smaller proportion achieving "very good" performance. Conversely, the experimental group demonstrated a higher concentration of students in the "very good" and "excellent" categories, including three students reaching the highest performance level.

This distributional shift toward higher achievement levels in the experimental group suggests not only statistical significance but also pedagogically meaningful improvement.

C. Inferential Statistical Analysis

Normality of post-test scores was assessed using the Shapiro–Wilk test (Table 4). Results indicated that data from both groups followed a normal distribution ($p = 0.058$ for the experimental group; $p = 0.248$ for the control group). Homogeneity of variances was verified using Levene's test ($p = 0.461$), confirming equal variances and supporting the use of parametric analysis.

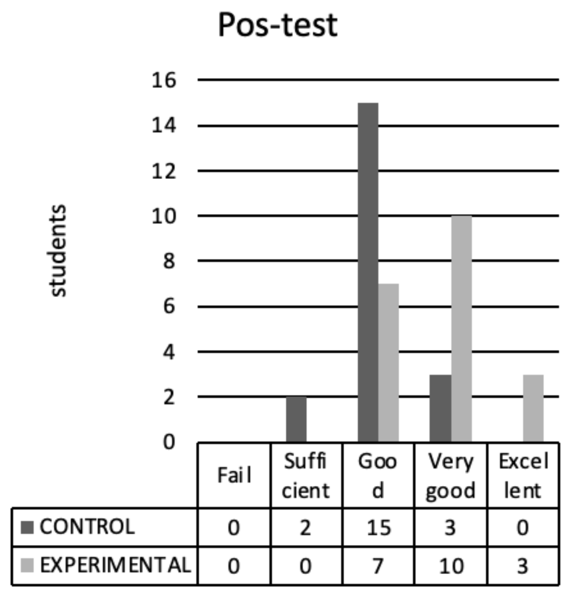

Figure 2. Quantity of students into grades in the evaluation process

Table 4
Shapiro–Wilk and Levene's tests for the post-test scores.

Group	Shapiro–Wilk (p)	Levene's Test (p)
Experimental	0.058	0.461
Control	0.248	—

Table 5
Independent Samples t-Test

Comparison	t	df	p-value
Experimental vs Control	4.073	38	0.001

The analysis revealed statistically significant differences between groups, $t(38) = 4.073$, $p = 0.001$, leading to the rejection of the null hypothesis. The mean difference of approximately 3.1 points in favor of the experimental group demonstrates a substantial instructional advantage associated with GeoGebra-supported learning.

To determine practical significance, Cohen's d was calculated, yielding a value of 1.48, which represents a large effect size according to conventional benchmarks ($d \geq 0.80$). This indicates that the observed improvement was not only statistically significant but also educationally meaningful.

These findings are consistent with prior research reporting significant performance gains associated with GeoGebra-based instruction [31], as well as improvements in conceptual retention in mathematics education contexts [9].

IV. Discussion

The findings of this study confirm that the implementation of GeoGebra significantly enhances learning outcomes in real variable functions, particularly during the initial stages of engineering education. The substantial difference observed between groups, together with the large effect size (Cohen's d = 1.48), indicates that the impact of dynamic software integration extends beyond statistical significance and represents a meaningful educational improvement. This magnitude suggests that dynamic visualization and interactive parameter manipulation significantly enhance representational fluency and support higher-order abstraction processes in mathematical reasoning.

The improvement observed in the experimental group can be interpreted through the lens of multi-representational learning. As highlighted by [13], the integration of algebraic and graphical representations facilitates deeper understanding of functions involving parameters, enabling students to establish stronger connections between symbolic expressions and their graphical behavior. In the present study, this representational flexibility likely contributed to the superior performance demonstrated by students exposed to GeoGebra-supported instruction. These results reinforce the idea that conceptual understanding in mathematics benefits from environments that allow dynamic exploration rather than static observation.

This study contributes to the existing GeoGebra research by explicitly structuring the instructional intervention within a multi-representational learning framework, ensuring a systematic and intentional articulation between symbolic and graphical registers. Unlike prior studies that primarily report performance improvements associated with the use of dynamic software, the present research makes explicit the pedagogical design underlying such improvements, including the criteria for function selection and the role of coordinated representational transformations. In doing so, this study not only provides empirical evidence of effectiveness but also advances a more transparent and replicable instructional model for teaching real variable functions in engineering education.

In this regard, the integration of GeoGebra was not limited to visualization support but functioned as a cognitive mediating tool that enabled students to dynamically transition between algebraic expressions and their graphical counterparts. This structured interaction between representations facilitated deeper conceptual processing, allowing learners to construct meaning through continuous comparison, validation, and reinterpretation of mathematical objects. Consequently, the findings of this study contribute not only empirical evidence of effectiveness but also a theoretically grounded explanation of how and why GeoGebra-supported instruction enhances learning, thereby advancing the current research landscape toward more replicable and pedagogically explicit intervention models.

Consistent with these findings, [40] emphasize that GeoGebra effectively supports the graphical representation of abstract calculus concepts, thereby facilitating advanced mathematical reasoning. Similarly, [41] report that the use of GeoGebra enhances procedural and conceptual understanding in differential calculus by promoting self-exploration and collaborative interaction, mechanisms that were also present in the instructional design of the experimental group in this study. The improvements identified here further align with the results reported by [34], who documented significant gains in students' understanding of mathematical functions when dynamic software tools were integrated into instruction.

Moreover, prior empirical research supports the robustness of these outcomes. For example, [13] found statistically significant differences between experimental and control groups when GeoGebra was incorporated into instruction, while [41] reported significant disparities using non-parametric analysis. Similarly, [31] demonstrated substantial performance differences in trigonometry learning through independent samples testing, with the GeoGebra group outperforming traditional instruction by a wide margin. Likewise, [11] concluded that students using GeoGebra not only achieved higher academic performance but also demonstrated improved graphical representation skills, particularly in collaborative settings. These studies collectively reinforce the conclusion that technology-assisted instruction, when pedagogically structured, does not merely complement traditional teaching but transforms the cognitive engagement with mathematical concepts.

The present results also resonate with findings reported by [9], who observed improvements in conceptual retention when GeoGebra-supported instructional materials were implemented. Although [9] focused on secondary education, the convergence of evidence across educational levels suggests that the cognitive benefits of dynamic mathematics environments are transferable to higher education contexts, particularly in foundational engineering courses.

From an educational perspective, these findings support the modernization of engineering curricula through the systematic integration of dynamic open-source technologies.

The use of GeoGebra aligns with broader goals of technology-enhanced STEM learning and contributes empirical evidence to ongoing post-pandemic digital transformation efforts in higher education. Furthermore, as an open-source platform, GeoGebra promotes equitable access to high-quality digital resources, which is particularly relevant in Latin American public universities where financial constraints may limit access to commercial software solutions.

Despite these positive outcomes, certain limitations must be acknowledged. The study involved a relatively small sample (n = 40) drawn from a single institutional context, and the intervention was limited to a six-week period. Additionally, although group equivalence was statistically verified, full randomization was not feasible due to institutional constraints. Future research should consider multi-institutional replication studies, larger samples, and longitudinal designs to evaluate the sustained impact of dynamic mathematics software on engineering students' conceptual development.

Overall, the results provide robust empirical support for the integration of GeoGebra in the teaching of real variable functions. The large observed effect size, together with alignment with previous literature, suggests that dynamic mathematical environments foster deeper abstraction, improved representational fluency, and enhanced learning outcomes in engineering education contexts.

V. CONCLUSION

The findings of this study demonstrate that the integration of GeoGebra into the teaching of real variable functions leads to significant improvements in first-year engineering students' conceptual understanding. Beyond the observed statistical differences between groups, the results highlight the importance of structured pedagogical design when incorporating dynamic mathematical software into instructional practice.

In particular, the effectiveness of the intervention can be attributed to the systematic articulation between symbolic and graphical representations, supported by dynamic visualization and parameter manipulation. This confirms that meaningful learning in mathematics is strengthened when students actively engage in multi-representational reasoning processes rather than relying on static and procedural approaches.

From an educational perspective, this study provides not only empirical evidence of the effectiveness of GeoGebra-supported instruction, but also a theoretically grounded and replicable framework for its implementation in engineering education. The explicit integration of pedagogical criteria and representational coordination offers a model that can be adapted to similar contexts in higher education.

Future research should explore the scalability of this approach across different institutional settings, larger sample sizes, and longer intervention periods, as well as its impact on other areas of mathematics. Additionally, further studies could examine the role of teacher training and digital competencies in maximizing the effectiveness of dynamic mathematical environments.

Overall, the integration of dynamic mathematical software, when supported by a clear pedagogical and theoretical framework, represents a promising pathway toward enhancing conceptual understanding and advancing technology-enhanced STEM education.

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