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Analyzing Students' Errors in Integral Calculus Through GeoGebra-Assisted Project-Based Learning

Diana Astria Gultom[1*]
Universitas Pelita Harapan Medan, Indonesia

Sahat Saragih[2]
Universitas Negeri Medan, Indonesia

Edi Syahputra[3]
Universitas Negeri Medan, Indonesia

***Corresponding author:**
Diana Astria Gultom, Universitas Pelita Harapan Medan, Indonesia.
✉astria.g12@gmail.com

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Abstract

Background: Students in higher education consistently demonstrate significant difficulties in integral calculus, particularly in selecting appropriate problem-solving strategies and executing procedural steps. Despite extensive research on mathematical errors, studies integrating *Newman Error Analysis* (NEA) with technology-enhanced, project-based pedagogy at the university level remain scarce.
Objective: This research aims to examine the types of errors students make in solving integral problems in calculus by implementing *Project-Based Learning* (PBL) using *GeoGebra* software.
Methods: The research adopted a descriptive qualitative method with 15 ACT students from the Informatics Department of *Universitas Pelita Harapan Medan*. Data were collected from written integral test items, observation sheets, and brief interviews with selected students. Errors made by students were classified according to the *Newman Error Analysis* (NEA) framework, which consists of reading, comprehension, transformation, process skill, and encoding errors.
Results: The findings suggest that the combination of PBL with *GeoGebra* enables students to visualize integral concepts dynamically and enhances their geometric understanding of both definite and indefinite integrals. The most frequent error was transformation (60%), followed by process skill (53.3%), comprehension (46.7%), reading (20%), and encoding errors (13.3%). These results indicate that many students continue to struggle with deciding how to integrate an expression and completing the correct computations. The method helped alleviate conceptual difficulties owing to the visualization features of *GeoGebra*.
Conclusion: *GeoGebra*-assisted PBL effectively supports error diagnosis and conceptual remediation in integral calculus. Integrating dynamic visualization with project-based inquiry reduces transformation and process skill errors by helping students connect symbolic procedures to geometric interpretations.

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INTRODUCTION

Calculus serves as a critical analytical framework in higher education, enabling students to examine rates of change, accumulation processes, and mathematical modeling across various scientific and technological fields. Integration is consistently identified as the concept in calculus with which university students struggle the most. Empirically, studies report that 60–75% of undergraduate students fail to correctly solve integral problems on first assessment (Harahap et al., 2025; Tall, 1993), with errors concentrated in strategy selection and procedural execution. In Indonesia specifically, national higher education assessment data (Ersyad et al., 2026) indicate that calculus failure rates in engineering and informatics programs exceed 40%, underscoring the urgency of developing evidence-based instructional models for this domain. These challenges extend beyond computational tasks to involve deep conceptual misunderstandings of what an integral actually represents. Often, students can perform the arithmetic operations of integration but cannot interpret what an integral means geometrically (as the area under or over a curve) or statistically (as a sum), or how it applies in physics and other sciences. This observation suggests an imbalance in current practices, favoring procedural over conceptual approaches.

Studies in mathematics education have identified various student errors in integral problem-solving. For example, errors may occur when understanding what a problem is asking, choosing an appropriate strategy, or performing mathematical calculations. Mistakes also arise when students write or interpret final answers. Learning errors in calculus are not solely grounded in computational skill; patterns of error also reflect students' conceptual development and their ability to match representations with underlying ideas that model these concepts.

Student errors can be systematically identified using the widely adopted Newman Error Analysis (NEA) framework. In this framework, errors are classified into five hierarchical stages: reading errors, comprehension errors, transformation errors (process skill errors), and encoding errors. Using this classification, researchers can identify the stages at which errors most frequently occur, providing a clearer picture of students' learning challenges and informing targeted remedial interventions.

The evolution of error analysis theory has been guided by parallel advances in educational technology, including dynamic mathematics software. Through GeoGebra, students can better visualize functions and the areas they integrate over, enhancing their conceptual understanding. GeoGebra's interactive features allow students to examine correspondences between symbolic and graphical representations of mathematical ideas from multiple perspectives.

Within integral learning, GeoGebra visually depicts how the area under a curve is gradually constructed from a limiting process. This animated depiction aids students in linking the concept of the definite integral to its geometric interpretation in an engaging and meaningful way, supporting conceptual comprehension rather than shallow procedural knowledge. However, findings on GeoGebra's effectiveness are mixed. While Arbain and Shukor (2015) and Hohenwarter et al. (2008) report significant gains in conceptual understanding, Kissane and Kemp (2012) caution that technological tools may reinforce procedural dependence if not integrated with conceptual scaffolding (Larbi et al., 2024; Siregar, 2025). This suggests that GeoGebra's effectiveness critically depends on the pedagogical design in which it is embedded a gap addressed in the present study by coupling GeoGebra with PBL and NEA-guided error analysis.

Integrating technology alone is insufficient; employing a learner-centered pedagogical approach is equally important for enhancing instruction. One such approach gaining traction in higher education is project-based learning (PBL). Engaging in real-world projects that require investigation, collaboration, and critical thinking, PBL empowers students to be active agents in their learning process. Students become active partners in knowledge construction rather than passive consumers of information.

This combination of PBL and GeoGebra can create enriched learning experiences. In a project-based approach, students are not taught mathematics passively. GeoGebra enables them to explore key concepts intuitively through interactive, dynamic graphs, supporting both conceptual understanding and procedural proficiency via appropriate data representation.

PBL (Project-Based Learning) is a constructivist instructional model that positions students as creators of their own learning pathways by engaging them in projects with real-world contexts. The Buck Institute for Education Thomas (1999) identifies the following key elements of PBL: driving question, sustained inquiry, authenticity, student voice and choice, reflection, responsibility, critique, revision, and public presentation of products (Eshun et al., 2026).

PBL also promotes motivation and real-world problem-solving within mathematics education (Kessler, 2007; Learning, 2013; Zhao, 2025). Numerous empirical studies indicate that PBL fosters the development of higher-order thinking skills, sustained motivation, and deeper conceptual understanding compared to traditional teaching methods (Capraro et al., 2013; Han et al., 2015; Ramankulov et al., 2026). These characteristics make PBL an appropriate methodology, particularly for complex topics such as integral calculus.

GeoGebra is dynamic mathematics software created by Markus Hohenwarter (2008) as part of his master's thesis at the University of Salzburg in 2001 (Hohenwarter, 2002; Roanes-Lozano & Solano-Macías, 2023). Since then, it has become a widely used platform for open-source mathematics learning worldwide. GeoGebra supports multimodal representations including numerical, graphical, and symbolic forms enabling students to better understand mathematical concepts (Dikovic, 2009; Siregar & Siregar, 2026).

For calculus instruction, GeoGebra allows students to dynamically visualize limits, derivatives, and integrals. Studies indicate that GeoGebra significantly aids students in understanding integration, particularly in interpreting the geometric meaning of integrals as areas under curves (Arbain & Shukor, 2015; Selvy et al., 2020; Siregar, 2025). Its most educationally valuable features include visualizations of Riemann sums and definite integrals, which facilitate conceptual comprehension.

Newman Error Analysis (NEA) was introduced by Anne Newman in 1977 as a diagnostic framework for analyzing errors in mathematical problem-solving (Assamah et al., 2026; Newman, 1977). NEA sequentially categorizes five levels of error as students' progress through a problem: (1) Reading Error failure to properly read the representations or key terms in a problem statement; (2) Comprehension Error failure to extract the meaning of the problem; (3) Transformation Error failure to select the correct operation; (4) Process Skill Error failure to accurately perform computational procedures; and (5) Encoding Error failure to convey the solution in the normative format expected for an answer (Siregar, 2025; White, 2010). NEA has been widely applied in Indonesian mathematics education research, including studies on misconceptions in algebra, trigonometry, and calculus.

Based on the above, this study aims to examine the types of student errors in solving calculus integral problems using the Newman Error Analysis framework within GeoGebra-assisted Project-Based Learning. The findings will illuminate common error patterns and the extent to which this blended approach fosters deeper understanding of integral calculus. Additionally, the study may serve as an alternative resource for mathematics educators and researchers in designing calculus instruction with improved conceptual clarity and reduced error prevalence.

Specifically, this study seeks to: (1) determine the dominant types of errors among students; (2) analyze how integrating GeoGebra with PBL influences student errors; and (3) provide recommendations for improving pedagogical strategies in calculus education. Prior research has applied NEA mainly at the secondary school level (e.g., (Clarkson, 1991; White, 2010)) and has examined GeoGebra or PBL independently in higher education mathematics (Arbain & Shukor, 2015; Capraro et al., 2013; Siregar, 2025). No. previous study has simultaneou sly employed all three frameworks NEA as an analytical lens, GeoGebra as a visualization scaffold, and PBL as a pedagogical structure within a university-level integral calculus context. This study addresses that gap by developing an integrated diagnostic-pedagogical model applicable to undergraduate mathematics instruction in developing-country higher education.

It is anticipated that the results will provide both theoretical and practical contributions. Theoretically, this research advances the application of NEA in higher education and demonstrates the interplay between technology and pedagogy in shaping learning outcomes. Practically, the findings guide educators in creating more effective and engaging calculus experiences by thoughtfully integrating visualization tools and student-centered learning sequences. From error analysis to deeper comprehension of integral calculus, addressing student mistakes requires integrated strategies. The study represents a novel method for enriching mathematics education and enhancing students' preparation for contemporary societal challenges.

METHOD

This study employed a descriptive mixed-methods design (Creswell & Creswell, 2017; Rambharose, 2026), integrating qualitative error analysis with descriptive quantitative frequency data. The primary goal was not hypothesis testing but to richly describe and categorize the types of errors students made when solving calculus integral problems in a naturalistic learning environment. Quantitative frequency distributions (error counts and percentages) were used to identify dominant error patterns, while qualitative data from observations and interviews provided explanatory depth regarding the cognitive and procedural sources of those errors. The participants of this research were 15 third-semester students in the Department of Informatics, Universitas Pelita Harapan Medan, enrolled in the Calculus course for the academic year 2024/2025. The participants were determined using purposive sampling because this cohort was experiencing GeoGebra-assisted PjBL instruction in integral calculus for the first time. Prior to data collection, all participants were fully informed of the study's purpose, procedures, data handling protocols, and their right to withdraw at any time without consequence. Written informed consent was obtained from each participant. Participation was voluntary, and no academic penalties were associated with non-participation. The study was conducted in accordance with institutional ethical guidelines for educational research involving human participants.

The study follows a four-stage design: Preparation Stage – the development of a PBL-based course syllabus, GeoGebra modules, and assessment instruments; Instructional Stage – four weeks of GeoGebra-assisted PjBL sessions; Assessment Stage – administration of eight constructed-response integral test items; and Analysis Stage – examination of the quality of responses to the tests through Newman Error Analysis (NEA). Three instruments were used: (1) a constructed-response calculus integral test consisting of eight items, covering indefinite integrals, definite integrals, substitution techniques, and area calculations; (2) an observation sheet to record the PBL-GeoGebra instructional process; and (3) a structured interview guide to investigate students' reasons for errors. All instruments underwent content validity assessment by a panel of three validators: two calculus subject-matter experts and one mathematics education specialist. The Content Validity Index (CVI) was calculated for each item following the method of Polit & Beck (2006) and Takom et al. (2025). Items were rated on a four-point relevance scale (1 = not relevant to 4 = highly relevant). Item-level CVI (I-CVI) values above .78 were retained as the validity threshold. The Scale-level CVI (S-CVI/Ave) exceeded .90 for all three instruments, indicating strong content validity. Items receiving I-CVI below the threshold were revised per validator feedback before administration.

Data were analyzed following the three-phased model by Miles and Huberman (2014) and Takom et al. (2025): 1. Data reduction identification and classification of errors under NEA categories; 2. Data display construction of distribution tables showing the frequency and percentage of error categories; 3. Conclusion drawing interpretation of dominant patterns in terms of errors with suitable follow-up recommendations for instruction. Inter-triangulated data were used to establish interpretive reliability: test responses, observational records (field notes), and interview data collected from each student on the same selected 3×3 matrices.

In the teaching of integral calculus, this study employed Project-Based Learning (PBL) integrated with GeoGebra software. The goal of integrating this technology into instruction was to assist students in visualizing the mathematics and developing their conceptual understanding of systems while learning. By employing the Newman Error Analysis (NEA) framework, which classifies errors into categories of reading errors, comprehension errors, transformation errors, process skills errors, and encoding errors, the study examined students' mistakes in solving integral problems. The overall research framework used in this study is illustrated in Figure 1.

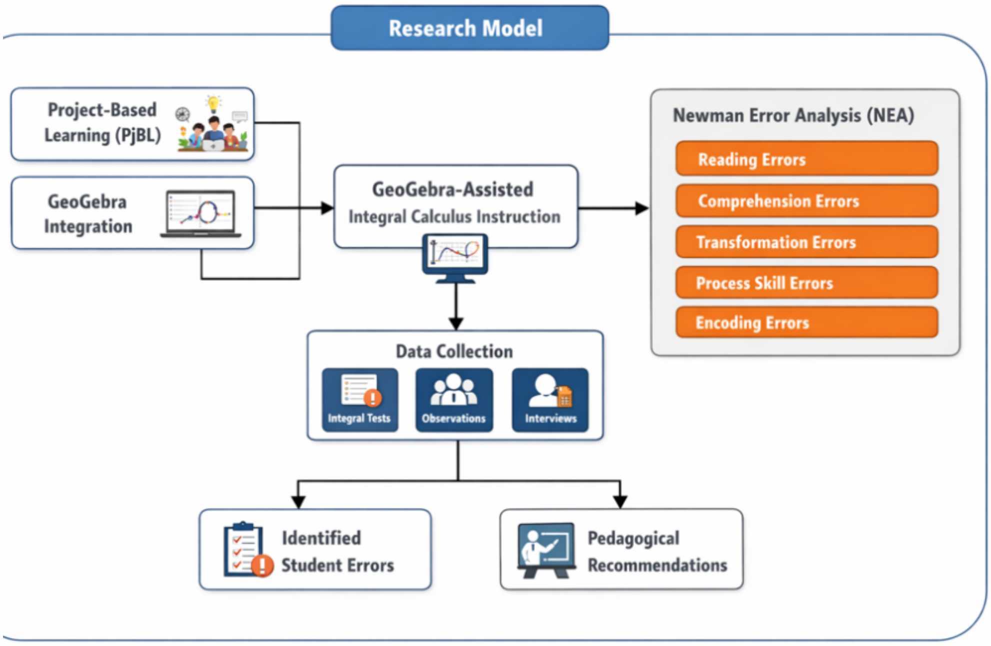


Figure 1. Research Model of GeoGebra-Assisted Project-Based Learning with Newman Error Analysis
Source: research data

RESULTS AND DISCUSSION

Implementation of GeoGebra-Assisted PBL

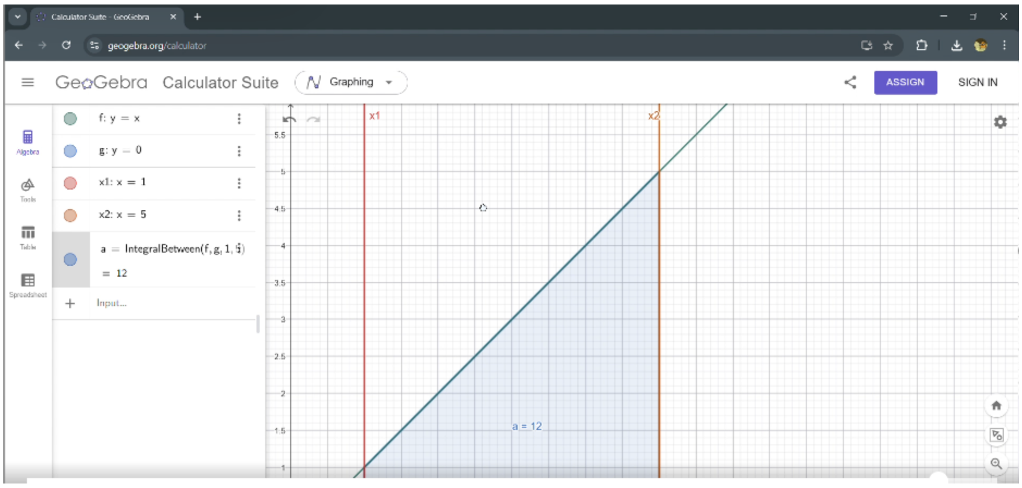
Data were collected through four sessions (4 × 100 minutes) of GeoGebra-assisted PBL instruction. The first session introduced the GeoGebra platform as well as the interpretation of integration as the area under a curve, utilizing dynamic visualizations of Riemann sums. Students appeared excited as they manipulated the limits of integration, observing how changing these values directly affected the numerical result of the definite integral. During the second session, students worked in groups of four or five to solve a mini-project that required applying integral concepts to calculate cross-sectional areas of structures related to architecture.

The third session focused on integration techniques, including substitution and integration by parts, with the use of GeoGebra to visualize and validate symbolic solutions. In the fourth and final session, all groups presented their projects along with GeoGebra visualizations of real-world applications of integral calculus within informatics contexts (e.g., computing areas in system response graphs).

Distribution of Student Errors According to NEA

A detailed analysis categorized students' errors into three main difficulties: (1) misunderstandings of the concept of area defined by curves; (2) procedural mistakes in determining the limits of integration; and (3) errors in graphically interpreting the relationship between functional graphs and integral expressions. Supporting students in visualizing functions and regions of integration was crucial in enhancing their understanding, and GeoGebra facilitated geometric visualizations.

Despite this support, some students struggled to connect the graphical representation of functions with the corresponding expressions for their integrals. It was common for students to have difficulty understanding the relationship between a function's graph and the region being integrated. GeoGebra was applied to assist in the visualization of functions and the area under a curve, which aided in the conceptual understanding of integral calculus. The integral represents the accumulation of quantities over a specific region, which students observed through dynamic visualization. Outputs produced by the students are illustrated in learning documentation using GeoGebra (Figures 2 and 3).



f: y = x

g: y = 0

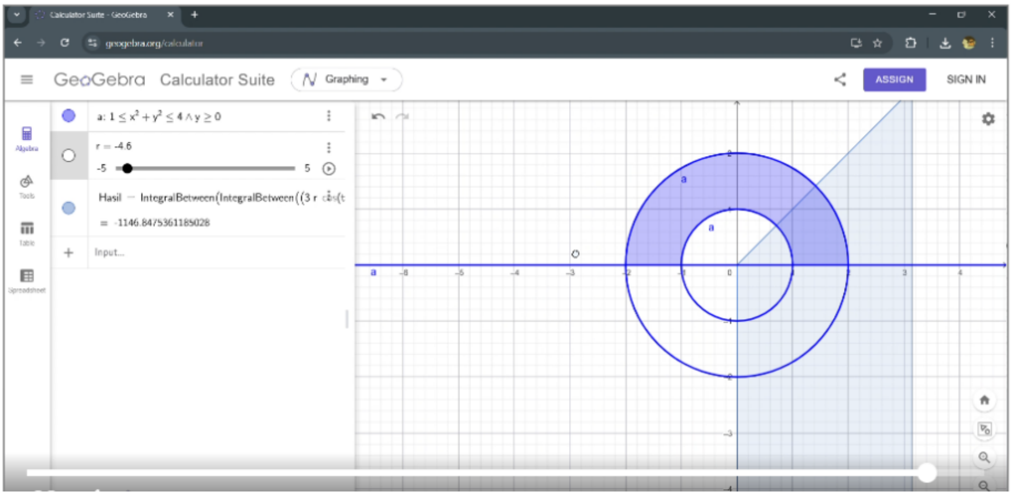
x1: x = 1

x2: x = 5

a = IntegralBetween(f, g, 1, 5)

= 12

Figure 2. Student solution using GeoGebra to illustrate the concept of integrals through a literacy-based approach.
Source: research data



a: $1 \le x^2 + y^2 \le 4 \wedge y \ge 0$

r = -4.6

Hasil = IntegralBetween(IntegralBetween((3 r cos(t

= -1146.8475361185028

Figure 3. Student solution using GeoGebra illustrating the transformation to polar coordinates in a double integral problem.
Source: research data

Error analysis was conducted to understand the types of mistakes students made when solving integral calculus problems. These errors were categorized using the Newman Error Analysis (NEA) framework, which includes reading errors, comprehension errors, transformation errors, process skill errors, and encoding errors. Table 1 presents the percentage distribution of students' errors across these five categories.

Table 1. *Distribution of Student Errors Based on Newman Error Analysis*

Error Category	Frequency (Students)	Percentage (%)	Primary Indicator
Reading Error	3	20.0	Incorrect reading of integral symbols or notation
Comprehension Error	7	46.7	Failure to interpret the meaning or information in the problem
Transformation Error	9	60.0	Incorrect selection of the integration method or technique
Process Skill Error	8	53.3	Errors in the computational procedure
Encoding Error	2	13.3	Errors in writing the final answer

Source: research data

Discussion

This category of transformation error was the most common, identified in 9 (60%) students. This type of error occurs when students understand the problem but have difficulty selecting an appropriate strategy or technique for integration. We identified three common types of errors: (1) using substitution methods on integrals that need to be solved by parts; (2) incorrect recognition of the substitution variable during integration; and (3) inability to recognize integral forms that correspond to a known formula or pattern. The dominance of transformation errors aligns with (Krieglstein et al., 2026; Sweller, 1988) cognitive load theory: when students' working memory is overloaded by the complexity of integrand structures, the strategy selection process is disrupted. This is compounded by the procedural-focused curriculum that emphasizes algorithmic rehearsal over conceptual strategy mapping (Scheiner et al., 2026; Star & Seifert, 2005). The lack of a flexible schema for method selection what (Sfard, 1991; Wedman & Bennet, 2025). calls the "operational conception" of mathematics explains why students apply familiar templates (substitution) even to problems requiring structurally different approaches (integration by parts). GeoGebra's graphical representation partially mitigated this by allowing students to visualize integrand behavior before committing to a strategy. In the case of $\int x\cdot\cos(x)\, dx$, most students attempted a simple substitution, $u = \cos(x)$, although integration by parts was the correct method. Interview data revealed that the majority of students were dependently applying memorized procedural templates without considering integrand function-designating aspects. GeoGebra's graphical visualization helped many students remediate these errors by displaying the integrand graphically along with its auxiliary variable, allowing more informed method selection to compute an integral.

Process skill error was found in 8 (53.3%) students. These errors include failure to follow procedural steps correctly in integral computation despite using the correct method. The most common procedural errors were: (1) sign errors, especially in the application of integration by parts; (2) algebraic manipulation mistakes, such as incorrect simplification of expressions; and (3) omission of the constant C in solutions of indefinite integrals. The graphical aspects of GeoGebra played a significant role in addressing this type of error. Students were able to identify potential computational mistakes and self-correct by comparing analytical results with the graphical output provided by GeoGebra. This self-correction mechanism is grounded in Duval (2006) theory of semiotic representation registers, which holds that mathematical understanding requires coordinated conversion between representational forms (symbolic, numerical, graphical) (Arnesen & Skartsæterhagen, 2025). GeoGebra operationalizes this coordination by providing simultaneous graphical feedback for symbolic computations, supporting students in developing Tall's (1993) "embodied conceptual understanding" of calculus (Harahap et al., 2025).

We identified comprehension error in 7 students (46.7%). This occurs when students can decode the mathematical symbols in a problem but cannot understand the underlying mathematics. The study determined three main indicators: (1) failure to interpret the definite integral as the area under a curve; (2) difficulty understanding the relationship between the integrand and the limits of integration; and (3) failure to ensure correspondence between a function's algebraic representation and its graphical representation. The Riemann sum visualization developed by GeoGebra directly addressed this gap, allowing students to visually see how the limit process yields the integral's value and maintains the relationship between numerical approximation and exact integration.

Three students (20%) committed reading errors, while the remaining 12 students (80%) correctly read and decoded the integral notation. Common reading errors included: not keeping track of the upper and lower bounds for a definite integral, misunderstanding the differential symbol dx as part of the integrand, and misreading parentheses in mathematical formulas. The least common classification was encoding error (2 students; 13.3%). The three common mistakes were: (1) forgetting to include the constant C in the solution of an indefinite integral; (2) failure to simplify the final expression; and (3) omitting units or contextual interpretation in applied problems.

GeoGebra facilitated error reduction through four main channels, based on observational records and interview data. First, the Riemann sum visualization helped students develop an intuitive understanding of integration as finding the area under a curve. Second, presenting the integrand directly in graphical format allowed students to develop an intuitive feel for the function prior to method selection. Third, the Computer Algebra System (CAS) feature enabled rapid verification of integral results. Fourth, through the Project-Based Learning (PjBL) design, GeoGebra provided a contextualized learning experience that enhanced students' understanding of the relevance of integral concepts in real-world applications. These results support the case for technology integration in mathematics instruction to enhance conceptual understanding, consistent with previous works by Selvy et al. (2020), Arbain and Shukor (2015) and Siregar (2025).

A notable contribution of this study is the simultaneous integration of GeoGebra-assisted Project-Based Learning (PBL) with NEA-based diagnostic error analysis in a university calculus context. However, without a pre-test/post-test design or a control group, this study cannot make causal claims about error reduction attributable to the intervention. The reported error frequencies reflect students' performance after exposure to the integrated instructional approach and should be interpreted as diagnostic benchmarks rather than evidence of comparative effectiveness. GeoGebra provides a dynamic visual of integral concepts and descriptively connects students to both symbolic and graphical representations. This result aligns with Arbain and Shukor (2015) and Selvy et al. (2020), supporting GeoGebra as a tool for improving students' conceptual understanding and mathematical thinking (Zuhaida et al., 2025).

Additionally, PBL offers students opportunities to actively engage in problem-solving activities, collaborating with peers to solve problems that relate and connect mathematical concepts to real-life situations. This aligns with findings by Capraro et al. (2013) and Han et al. (2015), who reported that PBL supports higher-order thinking and deeper learning (Ramankulov et al., 2026). The results demonstrate the developmental advantages of using PBL in conjunction with software such as GeoGebra.

From a theoretical standpoint, this study contributes to the literature on error analysis by providing further evidence of a link between forms in higher education mathematics and the NEA framework, which may be used for diagnosing student errors. While NEA has been widely applied in basic and secondary education, its utilization in university-level calculus offers new insight into foundational errors as they progress to higher-order problems. The results underscore the importance of developing conceptual understanding before transitioning to procedural techniques in mathematics instruction. Educators should systematically integrate visualization tools like GeoGebra to help students grasp abstract concepts. Moreover, project-based approaches increase student engagement and create relevant learning experiences.

Nonetheless, this study has several limitations. The sample size was small (15 students), restricting the generalizability of the findings. Moreover, it was a single-center study with a limited duration. Future research should include larger, more diverse samples and investigate the long-term effects of GeoGebra-assisted PBL on student learning outcomes. Additionally, incorporating quantitative approaches may provide stronger empirical support for the efficacy of this instructional model.

CONCLUSION

This research produces several important findings about the application of GeoGebra-assisted Project-Based Learning in identifying student errors in solving integral calculus problems. The most common error category was transformation error (60%), followed by process skill error (53.3%), suggesting that most students still struggle to select appropriate integration strategies and perform accurate computational procedures. Forty-four percent of students exhibited comprehension errors, 20% had encoding errors, and 13.3% had reading errors.

The use of GeoGebra in a PBL context led to significant improvements in conceptual understanding. The dynamic visualizations that GeoGebra offers help students observe the relationships between algebraic and graphical representations, thereby fostering an understanding of integration as the area under a curve. This verification enabled students to autonomously identify computational mistakes. Through this approach, students were encouraged to explore mathematical concepts, collaborate with peers, and develop critical thinking skills in a contextualized manner. Instructors of calculus courses at the post-secondary level should consider consistently integrating GeoGebra as an interactive space for mathematical exploration rather than solely as a visualization tool.

Theoretically, this study extends Newman Error Analysis (NEA) beyond its original primary and secondary school contexts to university-level integral calculus, demonstrating the framework's diagnostic utility in higher education. The findings reinforce constructivist learning theory by providing empirical evidence that technology-mediated, project-based environments facilitate the progression from procedural to conceptual mathematical understanding. Practically, the integrated PBL-GeoGebra-NEA model offers a replicable pedagogical framework for diagnosing and remediating systematic errors in undergraduate calculus. Future research should: (1) employ experimental designs with pre-test/post-test measures and a control group to establish causal claims about error reduction; (2) expand sample sizes across multiple institutions to improve generalizability; (3) investigate longitudinal retention of conceptual understanding; and (4) examine the model's applicability in other advanced mathematics topics such as differential equations and linear algebra.

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AUTHOR CONTRIBUTION STATEMENT

The authors contributed to this study as follows: Diana Astria Gultom was responsible for conceptualization, writing the original draft, editing, and visualization; Sahat Saragih handled writing – review and editing, formal analysis, and methodology; Edi Syahputra provided validation and supervision. All analyses, interpretations, and conclusions were conducted solely by the authors, with AI tools used only for minor language editing and grammar checking. This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors, and the authors declare no conflict of interest.

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