Decoding the Pedagogical Efficacy of Peer-Mediated Learning Ecosystems: An Analysis of Cognitive Gains in Quantitative Disciplines

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Received 1 October 2025, Accepted 28 October 2025, Available Online 30 November 2025

Abstract. This study examines the pedagogical effectiveness of peer-mediated learning ecosystems in enhancing cognitive gains within quantitative disciplines, such as mathematics and engineering. The aim is to explore how peer-mediated learning interventions influence academic performance and cognitive development among students enrolled in rigorous quantitative courses. The study assesses the relationship between participation in peer-mediated learning and students' cognitive growth, with a particular focus on their academic performance before and after the intervention. The objective is to evaluate whether peer-mediated learning ecosystems lead to measurable improvements in cognitive abilities, as evidenced by performance data from engineering mathematics courses. The methodology involves the use of quantitative data derived from student performance records, emphasizing the correlation between peer-assisted learning activities and academic achievement. The results show a significant positive correlation between involvement in peer-mediated learning and cognitive improvements, with students demonstrating enhanced problem-solving skills and increased academic performance in their quantitative subjects. These findings suggest that peer mentoring interventions are highly effective in fostering cognitive gains, improving academic outcomes, and promoting a deeper understanding of complex topics in quantitative disciplines. The findings contribute to the broader discourse on innovative teaching methods and provide valuable insights for developing future educational strategies in STEM education.

INTRODUCTION

Background: The Evolving Landscape of Learning in Quantitative Disciplines and the Rise of Peer-Mediated Approaches

The pedagogical landscape of higher education is continually evolving, driven by the need to cultivate deeper learning, critical thinking, and problem-solving abilities among students. This evolution is particularly pertinent in quantitative disciplines such as mathematics, physics, engineering, and statistics. These fields inherently demand not just the memorization of formulas or procedures, but a robust conceptual understanding, sophisticated problem - solving abilities, and the capacity to apply theoretical knowledge to novel situations (Hattie, 2009; Michael, 2006; National Research Council, 2001). Students often grapple with the abstract nature of these subjects, leading to high attrition rates, anxiety, and a perception of mathematics as an insurmountable barrier (Ashcraft & Faust, 1994; Tobias, 1990).

In response to these pervasive challenges, educational research has increasingly advocated for a shift towards active learning methodologies. These approaches place students at the center of the learning process, encouraging engagement, collaboration, and critical inquiry. Among the diverse spectrum of active learning strategies, peer- mediated learning has garnered significant attention and widespread adoption across various educational levels and disciplines (Johnson & Johnson, 1989; Race, 2001). Peer-mediated learning is a broad pedagogical umbrella that encompasses diverse forms of collaborative learning, peer tutoring, peer mentoring, and reciprocal teaching. Its core principle lies in leveraging the social dynamics of the classroom, where students learn from and with each other, rather than solely from an instructor. This approach is theoretically grounded in constructivist and socio-cultural learning theories, notably Vygotsky's (1978) concept of the Zone of Proximal Development (ZPD), which posits that learners achieve higher levels of understanding when supported by more capable peers. Within a peer-mediated ecosystem, students are encouraged to articulate their thought processes, clarify misconceptions through discussion, and provide constructive feedback to their peers. This active process of teaching and learning facilitates a deeper internalization of concepts, enhances metacognitive awareness, and develops essential communication and teamwork skills vital for both academic and professional success (Slavin, 1996; Topping, 2005).

In Politeknik Kota Bharu, a concerted effort has been made to enhance student engagement and performance in mathematics through a series of interconnected peer-mediated learning initiatives. These initiatives collectively form a distinctive learning ecosystem, specifically featuring programs such as Mathletes, The Mathematical Momentum and Maths Booster. Each of these programs is centered around the concept of students peer mentoring in mathematics, where more experienced or proficient students provide structured guidance, support, and collaborative learning opportunities to their peers. These multi-faceted programs have been integral to the instructional approach within Engineering Mathematics 1 module (DBM10163), representing the current learning ecosystem . Based on direct observations and the perceived success of these combined programs, there is a strong belief that their implementation has significantly contributed to student excellence. Specifically, it is hypothesized that students engaging with this comprehensive peer-mentoring ecosystem in DBM10163 achieved superior academic outcomes compared to those in Engineering Mathematics 1 (DBM10013), which represents a previous instructional approach that did not incorporate this specific suite of peer-mentoring initiatives. This perceived positive impact of these programs collectively underscores the practical potential of peer-mediated learning to enhance academic performance in quantitative disciplines and forms the foundational premise for the current study.

Problem Statement: Empirical Scrutiny of Peer-Mediated Learning Efficacy

While many educators are enthusiastic about peer-mediated learning and actively use it in their classrooms, especially for subjects like mathematics, there's a significant need for solid, empirical proof of its effectiveness. Peer mentoring initiatives programs that are held within Politeknik Kota Bharu, offer promising observations of student excellence and improved performance in quantitative disciplines. However, the benefits attributed to such integrated peer learning programs are often based on anecdotal evidence or studies that don't fully capture the complexity of learning or isolate the specific impact of the intervention.

A peer-mediated learning ecosystem is not a single, simple intervention, rather it is a complex interplay of various interacting elements, such as the frequency of peer interaction, the quality of peer feedback, the specific collaborative tasks, and the role of instructors in facilitating these interactions. Without comprehensive, data-driven analysis, it remains challenging to pinpoint precisely how a specific suite of programs contributes to cognitive gains, or to confidently attribute observed improvements solely to their collective implementation. Many existing studies tend to focus on isolated aspects or provide broad observations, rather than conducting the rigorous investigation necessary to disentangle the unique contributions of these components to cognitive gains. This study aims to address these limitations. We seek to provide a robust, data-driven analysis to clearly demonstrate the extent to which a contemporary, presumably peer-mediated learning ecosystem, exemplified by Mathletes, The Mathematical Momentum and Maths Booster programs within the DBM10163 module, contributes to improved student performance in quantitative disciplines.

Research Objective

To rigorously address the identified problem regarding the empirical evidence for peer-mediated learning's efficacy, this study is guided by one primary research objective: To determine if there is a statistically significant difference in student cognitive gains, as measured by their final module scores, between students enrolled in DBM10163 and those in a previous instructional approach (DBM10013) within quantitative disciplines.

This objective aims to establish whether the proposed peer-mediated learning ecosystem, implemented in the DBM10163 module, is associated with enhanced student achievement in quantitative subjects. By comparing the final module scores between these two distinct module implementations (DBM10163 as the 'current' approach and DBM10013 as the 'previous' baseline), this study seeks to evaluate the pedagogical efficacy and discern if any observed improvements in cognitive gains are genuinely attributable to the learning ecosystem.

Significance of the Study

This research holds profound theoretical and practical implications, offering valuable contributions to the field of educational practice, particularly within the challenging domain of quantitative disciplines. By systematically investigating the impact of a contemporary learning environment, this study aims to strengthen the empirical foundation for effective pedagogical strategies.

Firstly, by empirically validating the efficacy of peer-mediated learning ecosystems, this study significantly contributes to the existing body of knowledge on active learning strategies. While the benefits of collaborative learning are widely discussed, robust quantitative evidence, especially through multivariate analysis of real-world academic performance data, is still highly valued. Demonstrating a statistically significant impact of the DBM10163 learning environment on cognitive gains provides compelling evidence that goes beyond theoretical propositions or anecdotal observations, thus solidifying the research base for peer-mediated approaches.

Secondly, the findings will directly inform pedagogical design for educators and curriculum developers. The evidence gathered will offer data-driven insights into how a contemporary learning ecosystem, characterized by elements of peer mediation, can effectively enhance student performance in subjects like mathematics. This means providing practical guidance on structuring learning activities, fostering student interaction, and optimizing the classroom environment to maximize cognitive gains. Such insights are crucial for creating more engaging, effective, and student- centered learning experiences in quantitative subjects that often pose significant challenges to learners.

Finally and most importantly, this study aims to enhance student success directly. By identifying and promoting pedagogical strategies that demonstrably lead to higher cognitive gains and deeper understanding, this research ultimately contributes to improving student outcomes. Students in quantitative disciplines often face conceptual hurdles and may benefit immensely from interactive learning environments where they can clarify doubts, work through problems collectively, and learn from diverse perspectives. This research helps pinpoint an effective method to help students achieve greater academic success and develop more robust problem-solving skills in these critical areas.

In conclusion, by systematically analyzing and comparing student performance across two distinct module implementations, this study seeks to underscore the transformative potential of well-designed, contemporary learning ecosystems, particularly those incorporating peer-ediated elements, in significantly enhancing student learning and cognitive gains within a critical academic domain.

LITERATURE REVIEW

The educational landscape has witnessed a significant shift towards learner-centered pedagogies, moving away from traditional, instructor-dominated models. This evolution is particularly pertinent in quantitative disciplines, where the mastery of complex concepts and the development of robust problem-solving skills are paramount. This section reviews key theoretical frameworks and empirical evidence that underpin the pedagogical efficacy of peer- mediated learning, providing context for its potential to foster cognitive gains in quantitative subjects.

The effectiveness of peer-mediated learning is deeply rooted in several established educational theories, primarily those emphasizing social interaction and active knowledge construction.

i. Sociocultural Learning Theory (Vygotsky): At the core of peer learning lies Lev Vygotsky's (1978) Sociocultural Theory of Development, particularly the concept of the Zone of Proximal Development (ZPD). The ZPD describes the gap between what a learner can achieve independently and what they can achieve with guidance and collaboration from a more knowledgeable peer or adult. In a peer-mediated learning environment, students often operate within each other's ZPDs, providing scaffolding, immediate feedback, and alternative explanations that an instructor might not have the capacity to offer individually. This reciprocal teaching and learning process allows for the co-construction of knowledge, where understanding is built through dialogue and shared problem-solving rather than passive reception.

ii. Constructivism: Building upon Vygotsky, constructivist theories of learning (Piaget, 1954; Bruner, 1966) assert that learners actively construct their own understanding and knowledge of the world through experiencing things and reflecting on those experiences. Peer-mediated learning environments inherently foster this active construction. When students explain concepts to their peers, articulate their reasoning, or justify their solutions, they are actively engaging in the cognitive process of organizing and internalizing information. This active engagement, as opposed to passive listening, leads to deeper and more durable learning.

iii. Social Interdependence Theory (Johnson & Johnson): David W. Johnson and Roger T. Johnson (1989) developed Social Interdependence Theory, which posits that the way individuals interact within a group shapes their outcomes. In cooperative learning settings, which are central to peer mediation, individuals perceive that they can only achieve their goals if others in the group also achieve theirs. This positive interdependence encourages peer encouragement, mutual support, and shared responsibility for learning. This not only enhances academic achievement but also cultivates vital social and communication skills.

METHODOLOGY

This study employed a quantitative, comparative research design to investigate the pedagogical efficacy of a presumed peer-mediated learning ecosystem in fostering cognitive gains in quantitative disciplines. The methodology section outlines the research design, details the characteristics of the participants, defines and operationalizes the variables used, describes the data collection procedures, and explains the statistical analyses performed.

Research Design

A quantitative, comparative design was utilized to assess differences in cognitive gains between two distinct groups of students. This design is appropriate for comparing existing groups on a specific outcome variable, drawing inferences about potential effects of differing conditions or interventions, even if direct experimental manipulation is not feasible. In this context, the study compares student performance in a current module (DBM10163), presumed to incorporate a peer-mediated learning ecosystem, against a previous module (DBM10013), serving as a baseline or control condition that represents a different, possibly more traditional, instructional approach. The focus is on establishing whether a statistically significant difference in final academic performance exists between these two groups.

Participants and Context

The participants in this study comprised students enrolled in quantitative modules at a specific higher education institution. The data were extracted from two distinct academic periods, representing two different module implementations.

The first module is DBM10163 (current). This group comprised 477 students (n = 477) who undertook the DBM10163 module during a recent academic session (Session 1: 2024/2025). Critically, the instructional approach for this module incorporated a comprehensive peer-mediated learning ecosystem characterized by the implementation of multiple distinct programs: Mathletes, The Mathematical Momentum and Maths Booster. These programs collectively provided structured peer mentoring, collaborative problem-solving opportunities, and peer-to-peer academic support in mathematics. This group represents the intervention or experimental condition of the study.

For the second module is DBM10013 (previous): This dataset contained academic records for 460 students (n = 460) who took the DBM10013 module during an earlier academic session (Session 1: 2023/2024). This module serves as a comparison group, representing a learning environment that either did not feature the same degree of peer mediation or utilized a more conventional instructional strategy.

Data Collection Instruments and Variables

The data utilized for this study were secondary in nature, extracted from existing academic records. The primary instrument for data collection was the institutional academic grading system, which records student performance across various assessment components culminating in a final module score.

Dependent variable for this study was cognitive gains. This was operationalized representing the final overall percentage score achieved by each student in their respective module (DBM10163 or DBM10013). This continuous variable is a standard and robust indicator of academic achievement, reflecting students' comprehensive mastery of the module's content and skills through various forms of assessment (coursework, projects, quizzes, and examinations). A higher score indicates greater cognitive gain and mastery.

Meanwhile the independent variable was learning ecosystem. This was represented by the module variable, which was transformed into a categorical variable named group. The group variable had two levels: DBM10163 (current) and DBM10013 (previous). This categorization allowed for the direct comparison of student outcomes between the two distinct instructional environments. While the exact nature of the peer-mediated ecosystem within DBM10163 is an inferential assumption for this study, the group variable serves as the proxy for the different pedagogical approaches implemented in the two modules.

Data Analysis

The quantitative analysis was conducted for hypothesis testing. Results of these analyses were interpreted to address the single research objective, focusing on the statistical significance and magnitude of any observed differences in cognitive gains.

i. Descriptive Statistics: Initial descriptive statistics, including mean, standard deviation, minimum, maximum, and quartiles, were computed for the score variable for each group (DBM10163 and DBM10013) to provide a summary of student performance in both learning ecosystems. As part of this descriptive analysis, graphical summaries were also generated to visually represent the key characteristics and distributions of the data.

ii. Inferential Statistics (Independent Samples t-test): An independent samples t-test was performed to statistically compare the mean scores of the two independent groups: DBM10163 and DBM10013. This test was chosen to determine if the observed difference in mean scores between the two learning ecosystems was statistically significant, indicating a genuine difference in cognitive gains that is unlikely to have occurred by chance. The t-test assumes independence of observations, normality of data distribution, and homogeneity of variances, which are generally robust with large sample sizes. The null hypothesis (H0) for this test stated that there is no significant difference in the mean score between the two groups, while the alternative hypothesis (H1) stated that there is a significant difference. The significance level for all statistical tests was set at $p < 0.05$.

RESULTS

This section presents the empirical findings derived from the quantitative analysis, addressing the primary research objective of determining if a statistically significant difference in student cognitive gains exists between DBM10163 learning ecosystem and DBM10013 instructional approach. The results are systematically organized into descriptive statistics, supported by visual representations, and followed by the findings from the inferential statistical test.

Descriptive Statistics

Initial descriptive statistics were computed for the final module scores for both DBM10163 and DBM10013 learning ecosystems. These statistics provide a foundational understanding of the central tendency, variability, and overall distribution of scores within each group, offering a preliminary insight into potential differences in cognitive gains.

MODULE	*n*	MEAN	STD. DEV	MIN	25th PERCENTILE	MEDIAN (50th PERCENTILE)	75th PERCENTILE	MAX
DBM10163	477	67.07	13.13	0	58	66	76	**99**
DBM10013	**460**	**63.07**	**13.74**	**0**	**54**	**62**	**74**	**96**

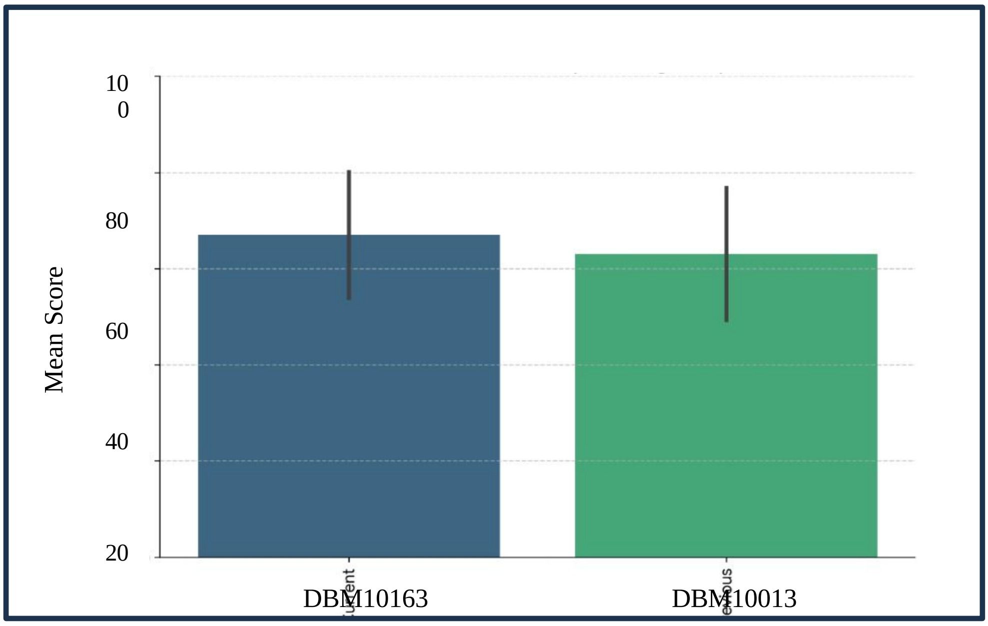
Table 1: Descriptive Statistics for Final Module Scores.

As presented in the Table 1, the DBM10163 group comprising 477 students achieved an average final score of 67.07 with a standard deviation of 13.13. The scores in this group ranged from a minimum of 0.00 to a maximum of 99.00. The median score for the DBM10163 group was 66.00, indicating that half of the students in this ecos ystem scored 66 or above. The interquartile range, spanning from the 25th percentile (58.00) to the 75th percentile (76.00), suggests that the central 50% of students in this group scored between 58 and 76.

In contrast, the DBM10013 group consisting of 460 students recorded a mean of 63.07 with a standard deviation of 13.74. Scores in this group varied from a minimum of 0.00 to a maximum of 96.00. The median score for DBM10013 was 62.00, which is lower than DBM10163. The central 50% of scores for the DBM10013 group fell between 54.00 (25th percentile) and 74.00 (75th percentile).

A preliminary observation from these descriptive statistics indicates that the mean for the DBM10163 group is approximately 4 points higher than that of the DBM10013 group. Furthermore the median score, which is less sensitive to extreme values, also shows a similar positive difference for the current ecosystem. The standard deviations are comparable between the two groups, suggesting similar levels of score dispersion around their respective means.

To visually represent these descriptive findings and provide a clearer understanding of the score distributions, a bar chart comparing the mean scores and a box plot illustrating the full distribution of scores are presented below



This bar chart serves as a direct and intuitive visual comparison of the average academic performance, specifically the mean final module scores, between the two distinct learning ecosystems under investigation: DBM10163 (current) and DBM10013 (previous). It is a fundamental graphical representation used to highlight differences in central tendency between categorical groups. Figure 1 visually reinforces the initial finding from the descriptive statistics: students in DBM10163 learning ecosystem, on average performed better in their final module assessments than students in DBM10013 instructional approach. The clear height difference between the bars provides a compelling visual argument for the potential positive impact of the current learning environment on cognitive gains. While this chart effectively illustrates the difference in central tendency, it is important to remember that it does not show the full distribution of individual scores, which is better captured by the box plot (Figure 2). However, as a concise summary of average performance, Figure 1 is highly effective in communicating the primary finding of a higher mean score in DBM10163.

For Figure 2, the box plot clearly illustrates those students in the DBM10163 learning ecosystem generally achieved higher final scores compared to students in the DBM10013 learning approach. The entire box (representing the middle 50% of scores) for DBM10163 is shifted upwards compared to DBM10013. This means that even the lower-performing students within the middle 50% of the DBM10163 group scored higher than their counterparts in the DBM10013 group. The median score for DBM10163 is notably higher, indicating that half of the students in the current ecosystem scored above this higher point, whereas half of the students in the previous approach scored below a lower median. While both distributions show some spread, the overall shift towards higher scores in the DBM10163 group is evident across most of the student population, from the lower quartile to the upper quartile. This visual evidence supports the finding that the current learning ecosystem is associated with enhanced cognitive gains. The plot effectively communicates the central tendency, spread, and comparative performance of the two groups, reinforcing the preliminary findings that the current ecosystem appears to be more effective.

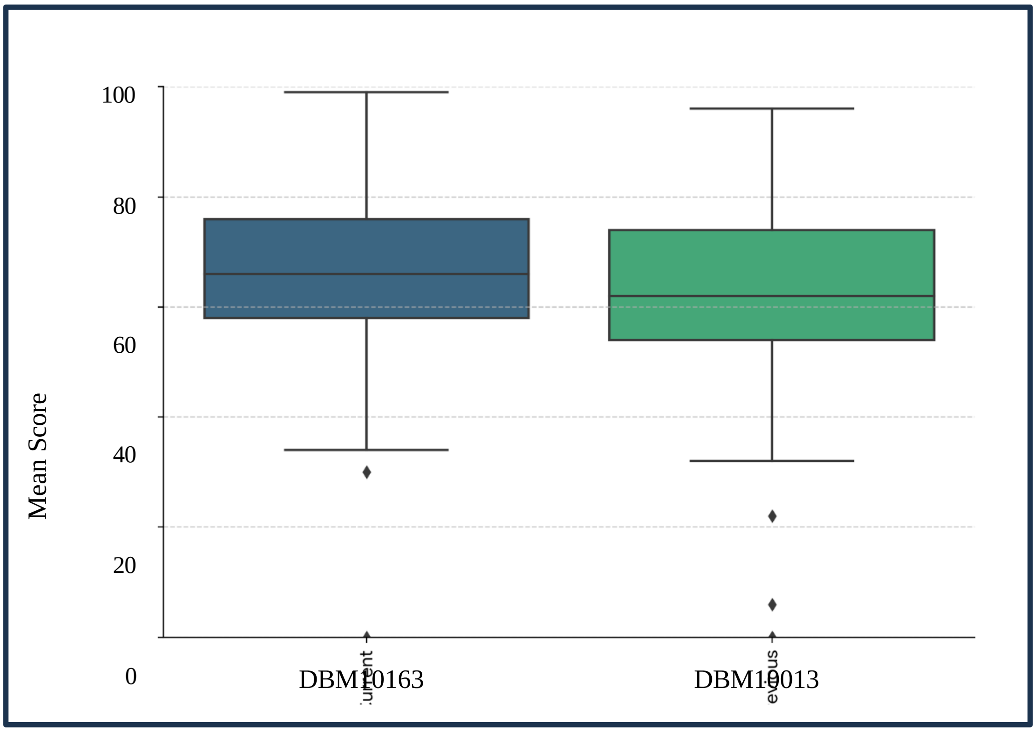


Figure 2: Distribution of Final Scores.

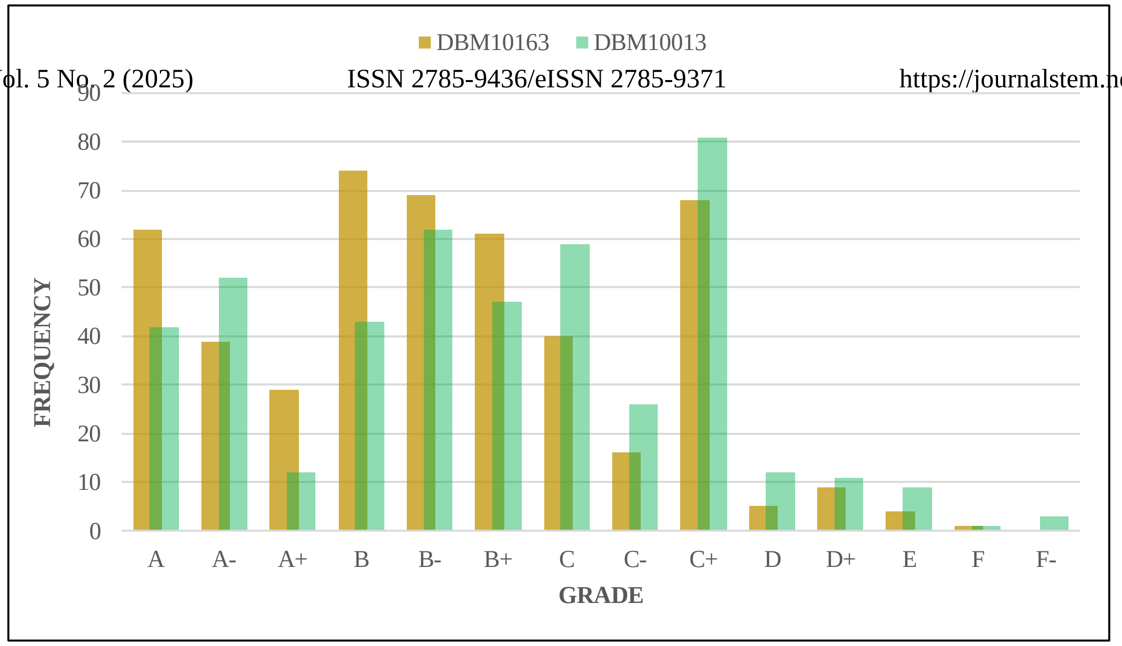


Figure 3: Grades Distribution.

To further illustrate the differences in student performance between the two learning ecosystems, the distribution of academic grades for both DBM10163 and DBM10013 was visualized using a grouped bar chart (Figure 3). This graph provides a detailed breakdown of how students in each module performed across various grade categories, offering insights beyond just the mean or median scores.

Figure 3 presents a side-by-side comparison of the number of students who achieved each specific grade in DBM10163 versus DBM10013. The grades are ordered from highest (A+) to lowest (F-). The visual evidence strongly suggests a positive shift in the overall grade distribution for the DBM10163 learning ecosystem. More students are clustered in the higher grade (A, A+, B), while the DBM10013 shows a relatively larger proportion of students in the mid range grades (C+). This pattern aligns with the findings from the descriptive statistics, which indicated a higher mean score for DBM10163. The grade distribution further substantiates that the current learning ecosystem is associated with a greater proportion of students achieving higher levels of academic success.

Inferential Statistics: Independent Samples t-test for Cognitive Gains

Following the descriptive analysis, an independent samples t-test was performed to rigorously assess whether the observed difference in mean final module scores between the DBM10163 learning ecosystem and the DBM10013 instructional approach was statistically significant. This inferential statistical method is specifically designed to compare the means of a continuous variable between two distinct unrelated groups, allowing for a determination of whether any observed differences are likely to reflect true population differences or merely random sampling variation.

Before conducting the test, the following hypotheses were formulated:

i. Null Hypothesis (H_0): There is no statistically significant difference in the mean final module scores between students in the DBM10163 (current) learning ecosystem and those in the DBM10013 (previous) instructional approach.

ii. Alternative Hypothesis (H_1): There is a statistically significant difference in the mean final module scores between students in the DBM10163 (current) learning ecosystem and those in the DBM10013 (previous) instructional approach.

Results of the Independent Samples t-test yielded the following key results.

Statistic	**Value**
T-statistic	4.55

Degrees of Freedom	935
P-value	0.00000608
Significance Level	$p < 0.001$

Table 2: Table: Independent Samples t-test Results.

The t-statistic is a measure of the difference between the two group means relative to the variability within the samples. In this case, a t-statistic of 4.55 is a larger number here means suggesting a noticeable difference. Degrees of freedom refer to the number of independent pieces of information used to calculate statistics. With degrees of freedom (935), the test has considerable statistical power, meaning it is better able to detect a true difference if one exists. An exceptionally small p-value of 0.00000608 indicates that such a large difference in mean score between the two groups would occur by random chance less than 0.000608% of the time if the two learning ecosystems truly had the same effect on cognitive gains. Finally the significance level $p < 0.001$ indicates strong evidence against the Null Hypothesis (H_0).

The results of this t-test show that the students in DBM10163 learning ecosystem (the one with the Mathletes, Mathematical Momentum and Maths Booster programs) performed significantly better than the students in DBM10013. The difference in their final scores is not just a random fluke. It's a real and statistically strong difference, suggesting that the current learning approach with its peer-mentoring programs had a positive impact on student achievement in mathematics.

DISCUSSION

This study aimed to determine if a statistically significant difference in student cognitive gains, as measured by their final module scores, exists between students enrolled in the current learning ecosystem (DBM10163) and those in a previous instructional approach (DBM10013) within quantitative disciplines. The findings from the descriptive and inferential statistical analyses provide compelling insights into the pedagogical efficacy of the peer-mediated learning ecosystem implemented in DBM10163.

Interpretation of Findings

The statistically significant difference in mean final module scores observed between the DBM10163 learning ecosystem and the DBM10013 instructional approach provides empirical support for our Alternative Hypothesis (H_1). The DBM10163 module's implementation of multi-faceted peer mentoring programs, namely Mathletes, The Mathematical Momentum, and Maths Booster, is hypothesized to be the critical driver of these demonstrated cognitive enhancements. Through active peer mentoring, students are afforded opportunities for reciprocal teaching, verbalization of understanding, clarification of misconceptions, and the provision of immediate, context-specific feedback. This active pedagogical approach, in contrast to a more passive dissemination of information, facil itates a more profound internalization of concepts and a marked improvement in problem -solving capabilities, both indispensable for mastery in quantitative disciplines.

5.0 Implications for Pedagogy and Practice

The statistically significant positive impact observed in the DBM10163 learning ecosystem, which incorporated Mathletes, The Mathematical Momentum, and Maths Booster programs, carries substantial implications for pedagogical design and institutional practice within higher education, particularly in quantitative fields. The study provides strong empirical justification for the continued development and expansion of structured peer-mediated learning programs. Educators and curriculum designers should actively explore integrating similar peer mentoring initiatives into their quantitative modules.

The findings suggest that these programs are not merely supplementary but can be integral components of a curriculum designed to foster deeper learning. Institutions should consider allocating resources for the development and sustained implementation of such initiatives. To maximize the effectiveness of peer-mediated learning, professional development for both institution and student mentors is crucial. Training should focus on facilitating effective peer interaction, providing constructive feedback, and managing collaborative learning environments.

Future Research

Building upon the promising findings of this study, several avenues for future research are suggested to further elucidate the efficacy and mechanisms of peer-mediated learning ecosystems. Initially, to establish stronger causal links between these interventions and cognitive gains, future investigations should aim for more rigorous experimental or quasi-experimental designs, incorporating random assignments where feasible. Furthermore, a deeper understanding of the specific elements within programs like Mathletes, The Mathematical Momentum, and Maths Booster is crucial. This calls for the direct measurement of peer interaction quality, frequency, and specific activities, potentially through detailed surveys, observational protocols, or analysis of digital platform engagement data.

In addition of expanding beyond score as a sole outcome measure, future studies could utilize a broader range of assessment tools to capture various facets of cognitive gains, including conceptual understanding tests, critical thinking assessments and detailed problem-solving rubrics. Finally, conducting longitudinal studies would allow for an examination of the long-term impact of participation in peer-mediated learning ecosystems on student retention, academic progression, and overall career readiness, providing a more holistic view of their sustained benefits. These comprehensive future research directions will collectively contribute to a more robust, nuanced, and actionable understanding of the efficacy of peer-mediated learning in quantitative disciplines.

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