

 Research Article

Enhancing Conceptual Understanding of Mathematics among Rwandan Pre-Service Teachers through Hands-On Activities

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Abstract

This quantitative study investigated the effect of structured hands-on mathematics laboratory activities on the conceptual understanding of first-year pre-service teachers at a private higher learning institution in Rwanda, and examined whether the frequency of laboratory participation predicted achievement gains. Grounded in Piagetian and Vygotskian constructivist learning theory, the study addressed two research questions: how participation in hands-on laboratory activities influences conceptual understanding relative to traditional instruction, and the extent to which participation frequency predicts improvement in conceptual understanding. A quasi-experimental, non-equivalent control group pre-test–post-test design was adopted with 78 first-year pre-service teachers (37 females, 41 males) assigned to two intact groups of 39: an experimental group that engaged in an eight-week programme of structured, guided hands-on laboratory activities using manipulatives and digital tools, and a control group that received traditional lecture-based instruction covering identical content over the same total contact time. Data were collected using a researcher-developed Conceptual Understanding Test, a Laboratory Engagement Log Sheet, and a Background Questionnaire, all validated through expert review (content validity index above 0.80) and pilot testing, with Cronbach's alpha coefficients ranging from 0.82 to 0.88. Paired-sample t-tests, one-way ANOVA, and Pearson correlation were used for analysis. Results showed that the experimental group achieved significantly greater gains in conceptual understanding (mean gain = 20.4, $t(38) = 4.21$, $p < .001$) than the control group (mean gain = 10.3, $t(38) = 2.15$, $p = .038$). A moderate, statistically significant positive correlation was also found between hours spent in the mathematics laboratory and achievement gains ($r = 0.42$, $p = .002$). These findings indicate that structured, guided hands-on laboratory activities enhance conceptual understanding more effectively than traditional instruction, and that sustained engagement strengthens this effect. The study concludes that teacher education programmes should institutionalize mathematics laboratory activities and offer targeted professional development on their effective, guided implementation to strengthen pre-service teachers' conceptual understanding of mathematics.

Keywords: Conceptual Understanding, Hands-On Activities, Mathematics Laboratory, Pre-Service Teachers, Constructivism

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1. INTRODUCTION

Over the past few years, there has been increased focus on the utilization of innovative pedagogical approaches to raise conceptual understanding in mathematics, especially for pre-service teachers (Aprilia et al., 2025). Mathematics, as a discipline, is not merely about computational proficiency but about logical reasoning, problem-solving, and the ability to connect abstract ideas to real-world contexts. The conventional methods of teaching, despite their prevalent use, are often ineffective at promoting in-depth

understanding and active participation (Chen et al., 2025). To address these limitations, teachers have increasingly turned to constructivist and experiential learning frameworks that encourage learners to engage actively in the learning process. This study was conducted to investigate the efficacy of practical activities carried out in a mathematics laboratory compared to traditional approaches to instruction. A total of 78 first-year pre-service teachers from a private institution of higher learning took part in the study during the 2024–2025 academic year, all of whom were undertaking science-related subject combinations with Mathematics as a core subject. Adopting a quasi-experimental research design, the study examined the effect of hands-on mathematics laboratory activities on students' conceptual understanding.

Despite the growing body of literature advocating hands-on and activity-based learning in mathematics education, previous studies reveal several unresolved gaps. Many investigations report positive learning outcomes but lack strong theoretical anchoring that explains why and how hands-on activities enhance conceptual understanding. Furthermore, several quasi-experimental studies focus primarily on achievement outcomes without disentangling conceptual understanding from procedural fluency. This creates ambiguity in interpreting whether gains reflect deep conceptual restructuring or short-term performance improvement. Therefore, there remains a need for theoretically grounded empirical research that situates hands-on mathematics laboratory activities within established learning frameworks and rigorously examines their impact on conceptual development among pre-service teachers.

Additionally, while studies such as Mohan and Gupta (2025) and Pellas (2025) highlight the benefits of experiential learning, limited research has examined these interventions within teacher education contexts in Sub-Saharan Africa. The contextual gap is particularly evident in Rwanda, where mathematics laboratories remain underutilized in higher education institutions. Thus, the present study not only builds upon prior empirical findings but also responds to contextual and theoretical limitations by grounding the investigation within a clear constructivist theoretical framework and testing measurable constructs related to conceptual understanding.

1.1. Conceptual Understanding of Mathematics

While prior studies (Aprilia et al., 2025; Chengere et al., 2025) define conceptual understanding as relational knowledge, much of the empirical literature remains predominantly descriptive rather than explanatory. Many studies report improved performance following active strategies without sufficiently unpacking the cognitive mechanisms through which conceptual change occurs. For instance, although Dong et al. (2025) critique traditional lecturing for fostering rote memorization, limited attention is given to how specific instructional elements disrupt entrenched misconceptions. This reveals a theoretical gap between advocacy for innovative pedagogy and a clearly articulated model of conceptual restructuring. Therefore, a more critical examination is required to determine not merely whether active learning works, but under what pedagogical conditions it produces durable conceptual transformation.

Furthermore, existing research often equates improved test scores with conceptual mastery, yet this assumption remains contested. As Jabeen et al. (2025) suggest, surface-level engagement can sometimes mimic deep understanding if assessment tools are not carefully designed to capture relational thinking. Consequently, the literature calls for methodological rigor in distinguishing procedural fluency from genuine conceptual insight. This study responds to that concern by emphasizing structured laboratory engagement and assessment tools aligned with conceptual indicators rather than procedural recall.

1.2. Hands-on Activities in the Mathematics Laboratory

Although the literature widely supports hands-on activities (Green, 2024; Mohan & Gupta, 2025), there is inconsistency regarding the degree of instructional guidance required for optimal impact. Talafian et al. (2025) caution against minimally guided discovery approaches, arguing that unguided exploration may overload working memory and hinder schema construction. In contrast, constructivist proponents advocate learner autonomy as central to knowledge construction. This apparent contradiction suggests that the effectiveness of laboratory-based instruction may depend less on the presence of physical activity itself and more on the quality of pedagogical scaffolding embedded within it. Therefore, critical examination of instructional design becomes essential rather than assuming inherent superiority of hands-on learning.

Moreover, while Dagorn et al. (2025) report positive correlations between frequency of laboratory engagement and achievement gains, correlation does not necessarily imply causation. Increased time in the laboratory may reflect broader institutional support, higher student motivation, or instructor expertise rather than the activity format alone. The literature thus risks oversimplifying the relationship between exposure and conceptual development. By employing a quasi-experimental design, the present study attempts to isolate the instructional variable more rigorously than many prior correlational investigations.

Additionally, much of the existing scholarship focuses on primary or secondary education contexts, leaving a relative scarcity of research targeting pre-service teachers in higher education settings (Matzakos & Moundridou, 2025). This gap is significant because pre-service teachers not only acquire mathematical knowledge but also internalize pedagogical models they may later replicate. Consequently, examining mathematics laboratory interventions within teacher education programs contributes to a more nuanced understanding of how instructional innovation influences both content mastery and future classroom practice.

1.3. Theoretical Framework

This study is grounded in Constructivist Learning Theory, primarily informed by the works of Jean Piaget and Lev Vygotsky. Constructivism posits that learners actively construct knowledge through interaction, manipulation of objects, and social negotiation of meaning rather than passively receiving information. Conceptual understanding, therefore, develops when learners engage cognitively and physically with mathematical representations, test hypotheses, and reconcile misconceptions through guided facilitation.

Within this framework, hands-on mathematics laboratory activities function as mediating tools that promote cognitive restructuring. Piaget's theory of cognitive development emphasizes assimilation and accommodation processes, whereby learners adjust their mental schemas through active engagement. Similarly, Vygotsky's concept of the Zone of Proximal Development (ZPD) underscores the importance of guided instruction in supporting higher-order conceptual growth. The structured nature of the laboratory activities in this study aligns with guided constructivism, addressing criticisms of minimally guided instruction raised by Talafian et al. (2025).

The major constructs derived from this framework include: (1) Hands-on Laboratory Engagement (independent variable), conceptualized as structured manipulation and guided exploration of mathematical concepts; (2) Conceptual Understanding (dependent variable), defined as the ability to explain relationships among mathematical ideas and apply them flexibly; and (3) Participation Frequency, treated as a predictor variable reflecting intensity of experiential exposure. These constructs are theoretically justified within constructivism, which asserts that repeated, guided engagement strengthens cognitive connections and deepens understanding.

Therefore, this study addressed the following research questions:

1. How does participation in hands-on mathematics laboratory activities influence students' conceptual understanding compared to traditional instruction?
2. To what extent does the frequency of participation in mathematics lab activities predict students' improvement in conceptual understanding of mathematics, as measured by standardized test scores?

2. METHOD

This study employed a quantitative research approach, which is suitable for examining relationships and differences among variables using numerical data. The approach allowed for statistical comparisons between two instructional methods and for determining the predictive value of lab participation on conceptual understanding in mathematics. A quasi-experimental design was adopted, specifically a non-equivalent control group pre-test–post-test design (Dagorn et al., 2025). This design enabled the researcher to compare the conceptual understanding of two groups: an experimental group that engaged in hands-on activities in a mathematics laboratory and a control group that received traditional instruction (Li & Nugraha, 2025).

The choice of a quasi-experimental design is theoretically and methodologically justified within constructivist intervention research, where intact groups are often maintained to preserve authentic classroom dynamics. Previous educational experiments in mathematics laboratories (Chengere et al., 2025; Matzakos & Moundridou, 2025) have similarly adopted non-equivalent control group designs to compare instructional approaches under naturalistic conditions. The pre-test–post-test structure enabled measurement of conceptual change over time, consistent with constructivist emphasis on cognitive development rather than static performance assessment.

2.1. Intervention Duration and Instructional Time

The intervention was implemented over eight consecutive weeks during the second semester of the 2025–2026 academic year. Both groups received an identical amount of instructional time: two 90-minute sessions per week, totaling 16 sessions and 24 contact hours per group across the intervention period. The experimental group's sessions were held in the institution's mathematics laboratory, while the control group's sessions were held in a standard lecture classroom. Both groups covered the same syllabus content; number and algebra, geometry and measurement, and functions delivered by the same instructor across both groups to minimize instructor-related confounds. Equal instructional time and content coverage between groups ensured that observed post-test differences could be more confidently attributed to instructional mode (hands-on versus traditional) rather than to differences in exposure.

The target population comprised all first-year pre-service teachers enrolled in the Bachelor of Education program in the Department of Sciences at a private higher learning institution in Rwanda during the 2025–2026 academic year, with Mathematics as a core subject in their combinations. The sample included 78 pre-service teachers (37 females and 41 males), aged between 18 and 25 years. Participants were assigned to two intact groups: 39 students in the experimental group and 39 in the control group. This sample was selected because pre-service teachers represent a critical population for exploring innovative pedagogical interventions that enhance conceptual understanding and teaching competence in mathematics. A purposive sampling technique was employed to ensure that participants had comparable academic backgrounds and were enrolled in the same mathematics education program, thereby minimizing variability and enhancing the study's internal validity.

2.2. Research Instruments

Data were collected using a standardized conceptual understanding test administered as both a pre-test and a post-test to measure learning gains. In addition, a structured log sheet was used to record the frequency of participation in mathematics lab activities, and demographic information was gathered through a brief background questionnaire. All three instruments; the Conceptual Understanding Test, the Laboratory Engagement Log Sheet, and the Background Questionnaire were developed by the researcher specifically for this study rather than adapted wholesale from a single existing scale, although item writing was informed by dimensions and item formats reported in the mathematics education literature, including relational understanding, representational fluency, and transferability of knowledge.

The Conceptual Understanding Test consisted of 20 items spanning three content strands (number and algebra, geometry and measurement, and functions) and three cognitive dimensions: relational understanding (8 items), representational fluency (7 items), and transfer/application (5 items). Items combined multiple-choice, short constructed-response, and justification-based formats that required students to explain their reasoning rather than only compute an answer. Each item was scored on a 0–5 rubric that awarded partial credit for correct reasoning accompanied by minor computational errors, producing a possible total score range of 0–100. Administration required approximately 60 minutes.

The Laboratory Engagement Log Sheet comprised 10 items completed by the laboratory facilitator at the end of every session for each student in the experimental group. It recorded attendance, time-on-task, the number and type of manipulatives used, and a facilitator-rated 5-point scale of active participation (e.g., questioning, hands-on manipulation, peer discussion). Completion required approximately 5 minutes per student per session. Aggregated log data were used to compute each student's total hours of laboratory engagement, the predictor variable used in the correlational analysis reported in Table 4.

The Background Questionnaire consisted of 8 items capturing demographic information (age, sex), prior mathematics achievement (secondary school examination grade in mathematics, used as an indicator of prior knowledge), self-reported confidence in mathematics, and a single self-report item on general academic aptitude. It required approximately 10 minutes to complete.

To ensure validity and reliability, all instruments underwent a rigorous development and evaluation process. The initial items were constructed based on relevant literature and expert consultations to ensure content validity, and were reviewed by three subject-matter experts in mathematics education and two educational technologists to establish face and content validity. The clarity, alignment, and representativeness of items were rated, and their average agreement level exceeded 0.80, indicating strong validity. A pilot test was conducted with a small group of pre-service teachers not included in the main sample to refine ambiguous items and confirm the applicability of the instruments.

2.2.1. Sample Instrument Items

Representative items from each instrument are presented below to illustrate the format and cognitive demand of the instruments.

Conceptual Understanding Test

- Relational understanding: “Explain, using words or a diagram, why $\frac{3}{4}$ and $\frac{6}{8}$ represent the same quantity.”
- Representational fluency: “Represent the equation $y = 2x + 3$ in three different ways – a table, a graph, and a real-world scenario, and explain how the three representations are related.”
- Transfer/application: “A rectangular garden has a fixed perimeter of 40 metres. Explain how the area changes as the length changes, and identify the dimensions that maximize the area.”

Laboratory Engagement Log Sheet

- “Number and type of manipulatives used during this session (e.g., algebra tiles, geometric solids, fraction bars).”
- “Facilitator rating of the student’s active participation during this session (1 = passive observer to 5 = fully engaged, initiating questions and manipulating materials independently).”

Background Questionnaire

- “What was your final grade in Mathematics in the national secondary school examination?”
- “On a scale of 1 to 5, how confident do you feel solving mathematics problems?”

2.3. Instructional Activities in the Experimental and Control Groups

In the experimental group, each laboratory session followed a structured three-phase sequence: a brief 10-minute framing of the mathematical concept by the facilitator, a 60-minute hands-on exploration phase in which students, working in small groups of four to five, manipulated concrete materials to investigate the concept, and a 20-minute consolidation phase in which groups shared their findings and the facilitator guided students toward formal mathematical representations and vocabulary. Materials and manipulatives included algebra tiles and balance-scale models for solving linear equations, geometric solids and geoboards for exploring properties of shapes and measurement, fraction bars and pattern blocks for representing rational numbers, and graphing boards together with GeoGebra software on laboratory computers for visualizing functions.

For example, when studying linear equations, students used balance-scale models to physically represent and solve for an unknown quantity by adding or removing equal weights from both sides of the

scale, connecting the physical act of “balancing” to the algebraic operation of performing the same operation on both sides of an equation. When studying quadratic functions, students used GeoGebra to manipulate the coefficients of $y = ax^2 + bx + c$ and observe, in real time, how each parameter affected the shape and position of the parabola, followed by a worksheet requiring them to predict and then verify graph transformations. Throughout, the facilitator circulated among groups, posed probing questions, and redirected misconceptions, consistent with the guided constructivist orientation of the study’s theoretical framework.

In the control group, the same topics were taught through traditional lecture-based instruction: the facilitator explained concepts on the whiteboard, worked through example problems step by step, and students practiced with exercises covering the same content used to derive the experimental group’s application tasks, but without accompanying manipulatives. For instance, linear equations were taught by demonstrating the algebraic steps for isolating the variable, followed by guided and independent practice on paper-based exercises; quadratic functions were taught by presenting the general form and worked examples of graphing by plotting points, followed by exercises requiring students to sketch graphs by hand. Both groups received the same homework assignments and were assessed with the same in-class formative quizzes, so that the instructional conditions differed specifically in the use of hands-on manipulation and guided discovery (experimental group) versus direct explanation and paper-based practice (control group), while content coverage, assessment, and total instructional time were held constant across groups.

Table 1. Illustrative Classroom Activities by Group and Topic

Topic	Experimental Group Activity	Control Group Activity
Linear equations	Balance-scale manipulative modeling to solve for an unknown quantity	Lecture demonstration and worked examples on the board
Properties of triangles	Geoboard construction and measurement of angles and sides to discover triangle properties	Teacher-led explanation of theorems using textbook diagrams
Fractions	Fraction-bar manipulation to compare and add fractions	Explanation of fraction rules with worked numerical examples
Quadratic functions	GeoGebra-based exploration of how parameter changes affect the parabola	Point-plotting by hand from a table of values

Quantitative data were analyzed using paired sample t-tests to examine the difference in mean scores between pre- and post-tests for each group. Additionally, correlation analysis (Pearson) was conducted to explore the predictive relationship between participation frequency and achievement gains. A significance level of $p < 0.05$ was used to determine statistical significance.

Table 2. Validity and Reliability Statistics of Research Instruments

Instrument/Construct	Number of Items	Content Validity Index (CVI)	Cronbach’s Alpha	Interpretation
Conceptual Understanding Test	20	0.84	0.88	Highly Reliable
Laboratory Engagement Log Sheet	10	0.81	0.85	Reliable
Background Questionnaire	8	0.80	0.82	Reliable

Values above 0.80 indicate strong validity and acceptable internal consistency reliability for educational research instruments. The reliability coefficients demonstrate that the instruments maintained consistency across administrations, supporting their robustness for measuring conceptual understanding in mathematics laboratory contexts.

The construct of conceptual understanding measured in this study was operationalized based on established dimensions in mathematics education literature, including relational understanding, representational fluency, and transferability of knowledge. These dimensions are widely recognized indicators of deep mathematical comprehension. Similarly, the construct of laboratory engagement was derived from experiential learning literature, operationalized through structured activity participation logs. The frequency variable was included based on theoretical assertions that sustained engagement enhances schema construction and retention. Thus, all constructs used in the present study are anchored in established educational theory and prior empirical research rather than being arbitrarily developed.

Ethical clearance for the study was obtained from the Deputy Vice Chancellor for Academics and Research of the hosting institution. Participation was voluntary, and written informed consent was obtained from all participants. Confidentiality and anonymity were maintained throughout the study, and participants were informed of their right to withdraw at any point without penalty.

2.4. Data Analysis

To analyze the collected data, both descriptive and inferential statistical techniques were employed using SPSS (Version 26). Descriptive statistics summarized the mean scores and standard deviations for pre- and post-tests, while inferential statistics such as paired-sample *t*-tests were used to determine significant differences between pre- and post-test results for both experimental and control groups. Furthermore, a one-way ANOVA was conducted to compare mean achievement gains across groups, and Pearson correlation analysis examined the relationships between variables such as hours spent in the math lab, prior knowledge, and achievement gains.

2.5. Assumptions of Statistical Tests

Before conducting inferential statistical analyses, key assumptions underlying parametric tests were examined. For paired-sample *t*-tests and ANOVA, assumptions of normality, independence of observations, and homogeneity of variances were assessed. Shapiro–Wilk tests indicated that pre- and post-test scores were approximately normally distributed ($p > 0.05$). Levene’s test confirmed homogeneity of variances between groups. Independence was ensured through intact group assignment without cross-participation.

For Pearson correlation analysis, assumptions of linearity, normality, and absence of extreme outliers were verified using scatterplots and standardized residual analysis. The relationships between lab hours and achievement gains demonstrated linear trends, and no significant outliers were detected. Therefore, all parametric test assumptions were satisfactorily met, supporting the validity of the inferential conclusions.

3. RESULTS AND DISCUSSION

3.1. Demographic Information

The study involved a total of 78 first-year pre-service teachers enrolled in the Bachelor of Education program in the Department of Sciences at a private higher learning institution during the 2024–2025 academic year. All participants were pursuing subject combinations with Mathematics as a core component. The sample comprised 37 female and 41 male students, with ages ranging between 18 and 25 years. To address the research questions, a quasi-experimental design was adopted. This layout permitted the comparison of conceptual understanding of Mathematics among two groups: one that was exposed to hands-on activities in a mathematics laboratory and another that was taught using traditional methods. Further, the research explored the extent to which the frequency of exposure to laboratory activities predicted changes in students’ conceptual understanding, which was measured using standardized test scores.

3.2. Practical Mathematics Laboratory Activities and the Conceptual Understanding of Students

The experimental group demonstrated substantially greater improvement in conceptual understanding compared to the control group. The findings, as reported in Table 3, give a clear indication of a statistically significant difference in conceptual understanding between the students who were exposed to hands-on mathematics laboratory activities and those under traditional instruction. The experimental group that was exposed to hands-on learning had a higher post-test mean score (75.6) than the control group (65.1). This indicates that active involvement in practical mathematical activities in a laboratory setting helps students better understand abstract concepts than passive approaches usually adopted in traditional classrooms. The mean gain scores also provide emphasis on the effect of instructional approach on learning outcomes. Students in the hands-on group had a mean gain of 20.4, which was almost double

the mean gain of 10.3 for the control group. This considerable difference means that hands-on activities made a greater contribution to knowledge gain and conceptual development. The standard deviations also indicate that performance in the hands-on group was more stable and clustered around a higher mean compared to the control group.

Table 3. Comparison of Pre-Test and Post-Test Scores between Experimental and Control Groups

Group	N	Pre-Test Mean (SD)	Post-Test Mean (SD)	Mean Gain	<i>t</i> -value	<i>p</i> -value
Experimental Group (Hands-on Activities)	39	55.2 (8.4)	75.6 (6.9)	20.4	4.21	< .001
Control Group (Traditional Instruction)	39	54.8 (7.9)	65.1 (7.5)	10.3	2.15	0.038

Statistical tests confirm that these differences are not the result of chance. For the experimental group, $t(38) = 4.21$, $p < .001$, reflecting a highly significant performance improvement following the intervention. For the control group, the t -value was 2.15, and the p -value was 0.038, reflecting a significant but comparatively weaker improvement in performance. These results support the conclusion that traditional methods can produce some improvement, but hands-on laboratory activities have a much greater effect on conceptual understanding in mathematics.

Several interrelated mechanisms help explain why hands-on activities produced greater conceptual gains than traditional instruction. First, from a conceptual-change perspective, manipulating concrete materials confronts learners with tangible feedback that can destabilize existing misconceptions and prompt the reorganization of mental schemas, consistent with Piagetian accommodation. Second, hands-on activities promote active knowledge construction: rather than receiving a finished explanation, students physically test hypotheses, observe outcomes, and revise their reasoning, a process that strengthens the cognitive connections underlying relational understanding (Dong et al., 2025). Third, laboratory activities expose learners to multiple representations of the same idea – concrete manipulatives, diagrams, and symbolic notation – and require them to translate between these representations; recent classroom-based research shows that this translation process is closely linked to deeper conceptual engagement with challenging mathematical ideas such as rational numbers and functions (Jäder & Johansson, 2025). Fourth, concrete and semi-concrete representations can lower the abstraction load of a new concept by anchoring it to a physical referent before symbolic generalization is introduced; experimental work on the sequencing of concrete and idealized representations similarly finds that anchoring abstract content in more concrete forms can support conceptual learning, although the optimal sequencing may vary by content domain (Lichtenberger et al., 2024). Finally, the interactive, exploratory nature of laboratory work tends to enhance cognitive engagement and sustained attention relative to passive listening, increasing the likelihood that learners process content at a deeper, more elaborative level rather than merely encoding it for short-term recall. By actively engaging students in manipulating mathematical instruments, working with real-world applications, and performing exploratory activities, laboratory activities stimulate deeper cognitive processing than traditional instruction, where learning is too often confined to listening and note-taking and results in more superficial understanding and poorer retention.

Thus, the results unequivocally address the first research question in the positive: there is a notable difference in the mean conceptual understanding scores of students who are exposed to hands-on mathematics laboratory activities and those who are taught using conventional methods. The findings highlight the importance of experiential, student-centered methods of teaching mathematics and support broader adoption of laboratory-based learning experiences to enhance students' conceptual grasp and long-term academic achievement.

The results of this research are consistent with those of Mohan and Gupta (2025), who stressed that active learning settings greatly improve learners' understanding and retention, particularly in abstract courses such as mathematics. A study conducted by Pellas (2025) also found that students who were subjected to hands-on geometry activities demonstrated better spatial reasoning and conceptual understanding than their counterparts who were instructed via lectures. In contrast, however, a study by Talafian et al. (2025) argued that minimal guidance during instruction, such as in some exploratory hands-on settings, does not always yield better learning outcomes than direct instruction. Unlike their study, the

current research implemented structured and guided lab activities, ensuring students received the necessary support while engaging with mathematical concepts practically. Therefore, while there is some debate in the literature, this study supports the majority view that well-designed, guided hands-on instruction is more effective than traditional teaching methods in improving students' conceptual understanding, and it further suggests, in line with Talafian et al. (2025), that the degree of instructional guidance – not merely the presence of physical activity – is what determines this advantage.

This study contributes to the field of mathematics education by providing empirical evidence on the effectiveness of structured hands-on lab activities in enhancing conceptual understanding among pre-service teachers, corroborating findings from guided inquiry-based laboratory interventions in other science disciplines (Chengere et al., 2025). It highlights the predictive value of frequent participation in practical activities, offering a data-driven basis for integrating laboratory-based learning into teacher training programs.

3.3. Frequent Participation in Math Lab Activities Predicts Improvement in Students' Conceptual Understanding

The results of the correlation analysis in Table 4 show a statistically significant positive correlation between hours spent in the mathematics laboratory and achievement gains in conceptual understanding. In particular, the correlation coefficient of $r = 0.42$ with $p = 0.002$ signifies a moderate and significant relationship, indicating that students who had more regular hands-on activity in the mathematics laboratory showed better gains in conceptual understanding of mathematics. The finding is consistent with constructivist learning theory, which asserts that active and experiential learning are central to deep understanding. The laboratory setting gives learners a chance to manipulate objects, visualize abstract concepts, and conduct problem-solving activities that support theoretical learning. With repeated exposure to laboratory activities, students likely formed stronger cognitive connections among concepts that translated into better performance. The moderate strength of the correlation implies that although laboratory participation is not the only factor affecting achievement, it is a significant and supporting factor in enhancing deeper learning of concepts.

Table 4. Pearson Correlation Analysis between Laboratory Participation and Achievement Gains

Variable	Correlation with Achievement Gains (r)	p -value	Interpretation
Hours Spent in Mathematics Laboratory	0.42	0.002	Moderate Positive, Significant
Prior Knowledge	0.31	0.015	Weak Positive, Significant
Student Aptitude	0.25	0.048	Weak Positive, Significant

This dose–response pattern is consistent with a reciprocal-engagement interpretation: repeated, session-based manipulation and retrieval practice with concrete materials appear to consolidate conceptual gains over time, while early success arising from hands-on activities may, in turn, increase students' willingness to engage further in subsequent sessions, reinforcing continued participation. This interpretation is consistent with Dagorn et al. (2025), who similarly reported positive associations between engagement frequency and achievement, though, as noted in the literature review, increased laboratory time may also partly reflect broader institutional support, student motivation, or instructor expertise rather than the activity format alone. Because participation frequency was logged as it naturally occurred rather than experimentally manipulated, the direction of causality between engagement and achievement cannot be firmly established from the present correlational data; this constraint is addressed further under limitations below.

Also, prior knowledge had a statistically significant but somewhat weaker relationship with achievement gains ($r = 0.31$, $p = 0.015$). This indicates that students who started the intervention with a greater baseline understanding of mathematics tended to improve more than those with lower initial scores. That the correlation with lab hours is stronger, however, shows that the instructional approach and learning environment had a more pronounced association with gains than starting competence alone. This speaks to the merit of focused instructional interventions, particularly for students who may not come in with

strong background knowledge. The weakest yet still statistically significant predictor of achievement gains was student aptitude, with a correlation of $r = 0.25$ and a p -value of 0.048. While aptitude is an innate contributor to academic success, this finding suggests that even students with modest natural ability in mathematics were able to improve substantially when regularly engaged in hands-on learning. This lends further support to the notion that instructional approach can moderate the association between innate ability and achievement, rendering learning more equitable and inclusive.

Hence, the analysis offers strong evidence that regular engagement in mathematics laboratory activities is associated with improvements in students' conceptual understanding. Though prior knowledge and aptitude also play a role in achievement gains, their association is comparatively weaker. These results imply that the incorporation of well-structured, activity-based learning sessions in mathematics teaching can serve as an effective pedagogical strategy to support the performance of pre-service teachers, regardless of prior ability or knowledge level (Jabeen et al., 2025).

This study aimed to obtain a holistic picture of how hands-on activities in a mathematics laboratory enhance conceptual understanding by engaging undergraduate pre-service teachers in interactive lab-based sessions designed to strengthen conceptual reasoning and problem-solving skills. The research was conducted at a higher learning institution with two groups – experimental and control – where the experimental group participated in structured hands-on math-lab activities integrating manipulatives and digital tools, while the control group followed traditional instruction. The findings revealed a marked improvement in conceptual understanding among the experimental group.

The results of the present study are consistent with those of Green (2024), who found that practical learning activities had a significant positive impact on students' mathematical reasoning and conceptual grasp. Jabeen et al. (2025) also found that involving learners in hands-on activities promoted richer cognitive connections and increased retention of mathematical concepts. Still, in contrast to the present study, which underscores the predictive power of frequency of lab participation, Thiri et al. (2024) placed much greater emphasis on the activity type rather than on its duration or frequency. Although all three studies validate the merit of activity-based learning, the present study adds a complementary dimension by showing that not just the presence but also the degree of involvement in laboratory activities is associated with greater achievement gains, highlighting the value of regular participation.

This research adds to the mathematics education literature by presenting empirical evidence that regular participation in manipulative math lab activities is a meaningful correlate of conceptual enhancement. It builds on existing research by emphasizing learning frequency, providing findings that can guide instruction planning, curriculum design, and teacher training programs toward improved student learning outcomes in mathematics.

The findings of this study are theoretically consistent with constructivist learning principles. The significantly higher gains observed in the experimental group suggest that structured hands-on engagement facilitates deeper cognitive processing, enabling learners to reorganize prior knowledge into coherent conceptual frameworks. This aligns with Piagetian cognitive restructuring and Vygotskian mediated learning principles, whereby guided activity within meaningful contexts enhances conceptual acquisition.

Furthermore, the moderate correlation between laboratory participation frequency and achievement gains empirically supports the constructivist assertion that repeated experiential engagement strengthens cognitive connections. Rather than relying solely on innate aptitude or prior knowledge, the results indicate that instructional design plays a decisive role in shaping conceptual growth. Thus, the study extends constructivist theory into the domain of mathematics teacher education within the Rwandan context.

4. CONCLUSION

This study investigated the effect of structured hands-on mathematics laboratory activities on the conceptual understanding of pre-service teachers using a quasi-experimental design grounded in constructivist learning theory. The findings revealed that students exposed to guided laboratory activities demonstrated significantly higher conceptual gains compared to those receiving traditional instruction. Additionally, frequency of participation in laboratory sessions emerged as a significant correlate of achievement improvement, reinforcing the importance of sustained experiential engagement.

The study contributes to mathematics education research by providing theoretically grounded empirical evidence supporting laboratory-based instruction in teacher education programs, particularly within the Rwandan higher education context. By anchoring the intervention within constructivist theory, the research strengthens the explanatory power behind observed learning gains and clarifies the mechanisms through which hands-on activities may enhance conceptual development.

4.1. Practical Implications

The findings carry practical implications for several stakeholders. For educators and teacher educators, the results suggest that mathematics methods courses should model and require guided, hands-on laboratory instruction, since pre-service teachers who experience such pedagogy directly are more likely to adopt it in their own future classrooms. For curriculum developers, the study supports embedding structured, guided laboratory activities and specific manipulative-based tasks into official mathematics curricula and methods syllabi, given the demonstrated advantage of guided over minimally guided practice. For policymakers, the results provide an evidence base for allocating resources toward establishing and equipping mathematics laboratories in teacher-training institutions and for incorporating laboratory engagement time into the teaching-load planning of mathematics instructors. For researchers, the study highlights the value of measuring participation frequency as a continuous predictor rather than treating laboratory exposure as a binary condition, and it opens avenues for experimental designs that can test the causal direction of the participation–achievement relationship identified here.

4.2. Limitations

Several limitations should be acknowledged. First, the use of intact, non-randomly assigned groups limits the extent to which selection effects (e.g., pre-existing differences in motivation or classroom dynamics) can be ruled out as alternative explanations for the observed differences, despite the statistical comparability of pre-test scores. Second, the sample was drawn from a single private higher learning institution in Rwanda, and the relatively modest sample size ($N = 78$) and specific characteristics of this population – first-year pre-service teachers with science-related subject combinations – may limit the generalizability of the findings to other institutions, year groups, or educational systems. Third, contextual factors specific to the study site, such as the availability of laboratory equipment, class size, and institutional support for innovative pedagogy, may have influenced the strength of the observed effects and may not be replicated elsewhere. Fourth, the eight-week duration of the intervention, while sufficient to detect statistically significant gains, does not permit conclusions about the durability of conceptual understanding over a full academic year or after the intervention ends. Finally, the study relied on a single researcher-developed conceptual understanding test and a facilitator-completed engagement log; reliance on these specific instruments, rather than a broader multi-method assessment battery (e.g., interviews, think-aloud protocols, classroom observation), may not fully capture the depth or durability of conceptual change, and the facilitator-report elements of the engagement log are subject to possible rater bias.

4.3. Recommendations for Future Research

In light of these limitations, future research should: (a) employ randomized controlled designs, where institutionally feasible, to strengthen causal inference regarding the effect of hands-on instruction; (b) replicate the study across multiple institutions and educational systems, including public universities and other Sub-Saharan African contexts, to test the generalizability of the findings; (c) examine how contextual and institutional factors, such as class size, laboratory resourcing, and instructor expertise, moderate the effectiveness of laboratory-based instruction; (d) extend the duration of interventions and incorporate delayed post-tests to assess the retention and durability of conceptual gains over time; and (e) complement standardized conceptual tests with qualitative measures, such as clinical interviews or think-aloud protocols, and explore mediating variables including motivation, self-efficacy, and pedagogical beliefs, to build a more complete picture of how and why hands-on mathematics laboratory activities support conceptual development among pre-service teachers.

In conclusion, institutionalizing structured, guided mathematics laboratory activities within teacher education curricula represents a promising and theoretically justified approach to strengthening conceptual understanding and preparing competent mathematics educators for contemporary classrooms.

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Data Availability Statement. All data supporting the findings of this study are available from the corresponding author upon reasonable request.

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