A Comparative Analysis of Computer-Aided and Traditional Teaching in Primary Mathematics: Evidence from Uzbekistan

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***Abstract*—This study investigates the effectiveness of Computer-Aided Instruction in enhancing mathematical understanding among primary school students, compared to traditional classroom teaching. The research focuses on two core topics—rounding decimal numbers and arithmetic operations with integers—and evaluates both short-term achievement and long-term retention. A controlled experiment was conducted with 272 students from Grade 5 and Grade 6 across one private and one public school in Uzbekistan. Students were randomly assigned to either a traditional classroom group or a computer-aided learning group, stratified by prior academic performance. Each group received a single instructional session, followed by a paper-based test one week later. A delayed retention test was administered to Grade 5 students after 100 days. Statistical analysis included non-parametric Analysis of Variance (ANOVA) and Chi-squared tests. Students in the computer-aided groups consistently outperformed those in traditional classrooms, with p-values below 0.0001. Higher average scores, reduced performance variability, and stronger retention were observed. The software's real-time feedback and random task generation enabled targeted teacher intervention and reinforced correct problem-solving strategies. The findings support that integrating Computer-Aided Learning into mainstream mathematics instruction, especially in resource-constrained settings, enhances learning outcomes without altering student–teacher ratios and offers scalable support for differentiated instruction. Future studies should include larger, more diverse samples and explore additional subjects. Incorporating adaptive difficulty and collaborative features may further improve outcomes. Limitations include the study's geographic scope, its single-session design, and reliance on quantitative measures.**

***Keywords*—Computer-Aided Learning (CAL), primary mathematics, instructional effectiveness, real-time feedback, automatic grading**

I. Introduction

In recent years, the integration of digital technologies into classroom instruction has reshaped the way mathematics is taught and learned. As educational systems strive to improve learning outcomes and address disparities in instructional quality, Computer-Aided Learning (CAL) has emerged as a promising tool for enhancing student engagement, comprehension, and retention. Mathematics, as a foundational subject in primary education, demands not only procedural fluency but also conceptual clarity [1]—qualities that can be reinforced through interactive and adaptive learning environments.

Traditional classroom instruction often relies on uniform pacing and generalized feedback, which may not adequately address individual learning needs. In contrast, CAL systems offer immediate feedback, adaptive task generation, and real-time performance monitoring, enabling educators to identify misconceptions and intervene with targeted support. These features align with contemporary pedagogical models that emphasize formative assessment, differentiated instruction, and learner autonomy.

The potential of Computer-Aided Learning (CAL) to improve mathematics education holds relevance in Uzbekistan, where the public school system continues to face challenges related to teacher shortages and uneven access to instructional resources. Official statistics highlight this issue, confirming over 1500 vacant positions in public schools as of 2025 (ish.mehnat.uz/vacancies). This environment makes the implementation of CAL especially important, as it offers a scalable solution capable of providing standardized, high-quality educational content, thereby mitigating the impact of staffing deficits and improving instructional equity across diverse geographic regions. This study responds to the need for empirical evidence on the effectiveness of CAL in improving mathematical understanding among primary school students, especially in comparison to conventional teaching methods.

This study is guided by the following research questions:

1) Does computer-aided instruction lead to higher immediate performance in mathematics compared to traditional classroom teaching among primary school students?
2) Does computer-aided instruction result in greater long-term retention of mathematical concepts?
3) How does the performance distribution differ between students taught using CAL and those taught using traditional methods?
4) What role does real-time feedback and adaptive task generation play in supporting student learning and teacher intervention?

The primary objective of this research is to evaluate the effectiveness of computer-aided mathematics instruction in primary education relative to traditional classroom methods for Grade 5–6 students in Uzbekistan. Specifically, the study aims to:

1) Measure and compare student performance across instructional modalities using standardized assessments.
2) Assess the impact of CAL on retention of mathematical concepts over one-week and 100-day periods.
3) Analyze performance distributions using non-parametric statistical methods to identify statistically significant differences between two groups.
4) Examine how CAL features—such as automated

feedback and progress tracking—support instructional decision-making and student engagement through survey responses.

The research hypothesis is "Students in the computer-aided learning groups exhibit significantly higher post-test scores than students in the traditional instruction groups one week after the initial instructional session".

This study contributes to the growing body of research on technology-enhanced learning by providing controlled, school-based evidence from a real-world educational setting. Its findings have practical implications for curriculum designers, school administrators, and policymakers seeking scalable solutions to improve mathematics instruction. By demonstrating the comparative advantages of CAL in both short-term achievement and long-term retention, the study supports the integration of digital tools into mainstream education without displacing the essential role of the teacher.

Moreover, the research highlights how CAL can address instructional gaps in resource-constrained environments, offering a pathway toward more equitable and personalized learning experiences. As educational systems worldwide continue to adapt to technological advancements, this study underscores the importance of evidence-based approaches to instructional innovation. The potential of CAL to improve mathematics education holds profound significance in Uzbekistan, particularly given the systemic challenges faced by the public school system. This operational environment makes the integration of CAL exceptionally relevant, as it provides a scalable solution capable of delivering standardized, quality educational content. By improving instructional equity across different geographic regions, CAL systems offer a direct pathway to addressing these structural issues. Therefore, this study directly responds to the need for empirical evidence demonstrating the comparative effectiveness of CAL in improving mathematical understanding among primary school students within this specific, resource-constrained context.

II. Literature Review

A large number of research papers have explored the comparative effectiveness of Computer-Aided Instruction (CAI) versus traditional teaching methods, particularly in mathematics and science education. Controlled experiments remain the dominant methodological approach, enabling researchers to isolate instructional variables and assess learning outcomes with statistical rigor.

Lashley [2] reported statistically significant gains in mathematics performance among the CAI group ($p < 0.01$). However, the small sample size and skewed data distribution raised concerns about the validity of t-test assumptions. Tantry and Sofi [3] examined academic achievement and retention among secondary school students, dividing 100 participants by intelligence level. Their results also favored CAI ($p < 0.01$), though the study lacked a longitudinal follow-up.

Mahawan [4] investigated conceptual understanding in Life Science using a structured nine-lesson online module. Their pre- and post-test analysis revealed significant gains in the CAI group ($p < 0.01$), reinforcing the value of interactive digital content. These findings are consistent with Zhang *et al*. [5], who found that students using interactive mathematics platforms demonstrated stronger retention and problem-solving skills than those taught via conventional methods.

Algarni [1] synthesized findings from multiple studies, confirming the overall effectiveness of CAI in mathematics instruction. Sung *et al.* [6] conducted a meta-analysis on mobile-integrated learning, concluding that digital tools consistently enhance learning performance across subjects. Son [7] provided a systematic review of intelligent tutoring systems, applying the SAMR model to classify instructional innovations and highlighting the pedagogical potential of adaptive technologies.

Bianchi *et al.* [8] analyzed China's nationwide CAI implementation in rural schools, where high-quality recorded lectures were distributed. Their longitudinal data showed that students exposed to CAI remained in school longer, adopted digital tools more frequently in adulthood, and performed better in the labor market. Ito *et al*. [9] conducted a randomized controlled trial involving over 1600 students using the "Think! Think!" program. The CAI group exhibited improvements in both cognitive and noncognitive skills, along with heightened aspirations for higher education.

Barrow *et al.* [10] evaluated the "I Can Learn ©" program across 17 schools with 1800 students over a full academic year. Their findings highlighted not only improved mathematics performance but also an accelerated learning pace in CAI environments. These outcomes align with recent meta-analyses of flipped classrooms, which revealed that technology-supported instruction consistently outperformed traditional models in STEM disciplines.

Several studies have emphasized the role of personalized feedback and engagement in digital learning environments. Tetzlaff *et al.* [11] proposed a classification framework linking feedback types to learning outcomes. Alzahrani [12] used structural equation modeling to show that student engagement in EFL online courses significantly predicted achievement, underscoring the importance of interactive course design. Safitri [13] explored collaborative digital learning, finding that virtual environments fostered deeper mathematical engagement.

Lee *et al.* [14] contributed to this discourse by reviewing current trends in learning analytics, highlighting how real-time data can inform instructional decisions and support personalized learning pathways. Their findings support the integration of analytics-driven feedback mechanisms, such as those used in the present study.

Meylani [15] conducted a systematic review on gamification in mathematics education, aligning its benefits with SDG 4 goals (ensure inclusive and equitable quality education and promote lifelong learning opportunities for all). The study found that game-based learning strategies enhanced motivation and performance, particularly in under-resourced settings. Dabingaya [16] further emphasized the role of AI-powered adaptive platforms in supporting differentiated instruction and improving mathematics achievement, especially among diverse learner profiles.

Balat *et al.* [17] assessed CAI's impact on early childhood concept acquisition, reporting significant post-test gains among preschoolers. Coymak [18] focused on metacognitive development, demonstrating that CAI improved students' ability to monitor and regulate their learning processes. These

findings suggest that digital instruction can support foundational cognitive skills and self-directed learning.

Graham [19] advocated for blended learning models, where digital tools complement teacher-led instruction. Hattie and Timperley [20] identified feedback as a critical driver of achievement, a principle echoed in CAI systems that offer immediate correction and reinforcement. Kim and Hannafin [21] emphasized scaffolding in technology-enhanced environments, bridging theory and practice to support problem-solving.

Hetmanenko [22] added to this body of work by highlighting the role of interactive learning in fostering student engagement and interest in mathematics. Her findings support the integration of dynamic instructional formats that promote autonomy and sustained attention.

Kizilcec *et al*. [23] found that feedback-rich environments in MOOCs contributed to durable learning and reduced achievement gaps. Adaptive digital instruction was shown to improve long-term retention of mathematical concepts.

The research available on the implementation of CAL and Information and Communication Technologies (ICT) within the educational systems of Central Asian countries covers a range of disciplines and academic levels. For instance, Rezuanova *et al.* [24] conducted an analysis of how computer-assisted instructional programs impacted the achievement and attitudes of university students towards language learning (Kazakh, English, and Russian), emphasizing the role of technology in a multilingual context. Temirkhanova *et al.* [25] focused on the pedagogical aspect, exploring the development of digital literacy among teachers at the Astana International School in Kazakhstan and how these skills influenced the effective instruction of subjects like Computer Science and Design to middle school students. Quantitative data were provided by Zhussupbayev *et al.* [26], who, in a study involving 66 high school students (33 in the experimental group and 33 in the control group), demonstrated the positive effect of CAL on student achievement and knowledge retention in the "History of World Civilizations" course. Specifically, the mean score of the experimental group after 12 h of CAL instruction was 19.3/30 compared to 16.1/30 in the control group; a retention test administered 28 days later also showed an advantage for the experimental group (16.15/30 versus 15.03/30). Furthermore, works by Ermetov *et al*. [27] and Begmatova [28] broaden the scope of analysis, addressing the importance of electronic education in higher education institutions and the application of distance learning at the preschool level, respectively.

Taken together, these studies provide a robust foundation for evaluating the pedagogical value of CAL. They consistently demonstrate that computer-aided methods not only enhance academic performance but also support broader developmental outcomes, including retention, metacognition, and equity. The present study builds on this literature by applying a controlled experimental design to compare CAL and traditional instruction in mathematics among primary school students in Uzbekistan, with attention to both short-term achievement and long-term retention. There exists a research gap in direct comparisons of the two teaching methods using identical instructional input. We aim to establish the advantage of CAL over traditional classrooms in practice sessions.

III. Materials and Methods

A. Design of Experiment

This study was structured as a controlled, school-based experiment aimed at evaluating the comparative effectiveness of computer-supported instruction versus traditional classroom teaching in primary mathematics education. The stratified randomized controlled quasi-experimental design was framed within a positivist paradigm, emphasizing objective measurement and statistical comparison.

The use of Computer-Aided Learning represents a critical shift from traditional instruction by fundamentally altering the dynamics of student practice and feedback. While conventional methods often provide generalized or delayed responses, CAL systems deliver immediate feedback, real-time performance monitoring, and adaptive task generation, which allow for the rapid identification of student misconceptions and support timely, targeted teacher intervention. These mechanisms are strongly rooted in constructivist theory, which posits that learning is an active process where individuals build new knowledge based on continuous reflection on their experiences. Specifically, the real-time feedback acts as an immediate scaffold, prompting students to actively reflect on their errors, test hypotheses about correct procedures, and construct a better understanding of the mathematical concepts in a self-directed manner, thereby promoting active learning and learner autonomy. This close alignment integrates CAL features with contemporary pedagogical models that prioritize formative assessment and differentiated instruction.

The instructional topics were selected based on their suitability for intensive practice and assessment: rounding decimal numbers for Grade 5 and arithmetic operations with integers—including negative values—for Grade 6. The topics chosen for instruction were fully aligned with the Uzbekistan National Standard for Mathematics for those specific grade levels.

The instructional sessions were designed to ensure consistency in content delivery while allowing variation in teaching modality. Each group received a single lesson focused on the specific mathematical topic aligned with its grade level: rounding decimal numbers for Grade 5 and arithmetic operations with integers—including negative values—for Grade 6.

Students in the traditional groups (T5 and T6) received instruction through direct teacher-led explanation. Correct solutions were demonstrated on the classroom whiteboard, followed by a guided practice session. Students completed exercises on paper, with opportunities for interaction and clarification from the instructor. Group T5 worked through a standardized set of 50 rounding problems sourced from the state-approved workbook, while group T6 completed 30 problems on integer operations, also drawn from the workbook. These exercises were selected to closely mirror the types of problems generated by the software used in the computer-aided groups.

Students in the computer-aided groups (C5 and C6) received the same initial explanation. Practice sessions were

conducted individually on computers, where each problem was presented sequentially with correct solutions displayed on their screens (Fig. 1). Group C5 completed 50 rounding problems, and group C6 solved 30 problems involving integer operations. The software provided immediate feedback for each response: correct answers were marked in green, while incorrect answers were marked in red and accompanied by the correct solution. This feedback mechanism was designed to reinforce accurate problem-solving strategies and prevent the consolidation of incorrect methods.

At the end of the session, students in the computer-aided groups completed an anonymous survey designed to capture their perceptions of the instructional method. The questionnaire allowed for multiple selections and open-ended responses, enabling students to identify which features they found most helpful.

To maintain the integrity of the experiment, teachers were instructed not to revisit the topics during the following week. All assessments were conducted under supervision, with high school students serving as invigilators to prevent academic dishonesty.

One week after instruction, all students completed a paper-based test under supervised conditions. A retention test was administered to Grade 5 students exactly 100 days later to assess long-term gains.

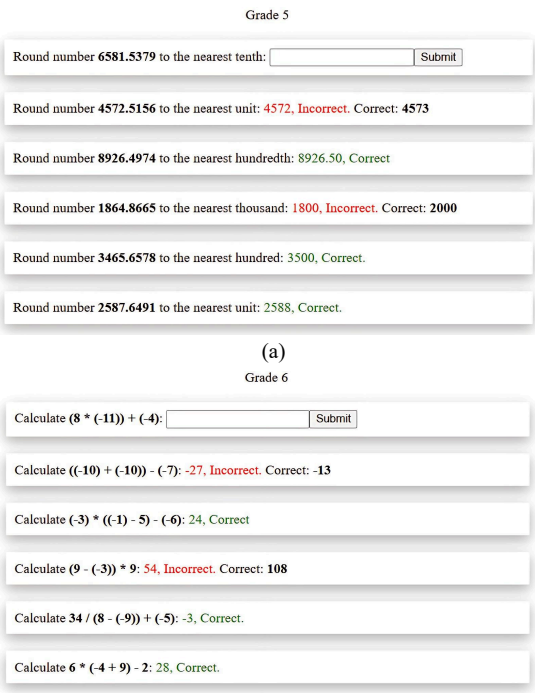


Fig. 1. Screenshots of the designed learning software interface. The current question appears at the top with an input field and a Submit button. The five most recent questions with student answers are shown below to support both learner reflection and instructor monitoring. (a) Rounding decimal numbers (b) Arithmetic operations with integers.

B. Sampling and Population

A total of 272 students from twelve Grade 5 and Grade 6 classes across one private and one public school in Tashkent, Uzbekistan participated. Specifically, 152 students from six Grade 5 classes and 120 students from six Grade 6 classes were included.

To ensure balanced initial performance across groups, students were randomly assigned to either the traditional classroom group or the computer-aided learning group based on their results on testing on the same topics before the instructions. Sampling followed requirements of a randomized trial. This stratified randomization helped maintain comparable baseline proficiency in both groups. The resulting cohorts were labeled as follows:

- T5: Traditional classroom group, Grade 5
- C5: Computer-aided group, Grade 5
- T6: Traditional classroom group, Grade 6
- C6: Computer-aided group, Grade 6.

C. Assessment and Testing Protocol

To evaluate the effectiveness of the instructional methods, a structured testing protocol was implemented. All students participated in a post-instruction assessment exactly one week after the initial lesson. The tests were administered on paper under supervised conditions, with no access to instructional materials or assistance. To ensure academic integrity, high school students were invited to serve as invigilators during all testing sessions.

Grade 5 students completed a set of 12 problems focused on rounding decimal numbers within 15 min, while Grade 6 students solved 10 problems involving arithmetic operations with integers, including negative values, within 20 min. The differences in the number of questions and time reflected the relative complexity of the mathematical operations required. All problems were designed to align with the content covered during the instructional session and were the same across groups to ensure comparability within each age division.

In addition to the post-test, a delayed retention test was conducted for Grade 5 students exactly 100 days after the initial lesson. This follow-up test was designed to measure retention and the long-term impact of the instructional approach. It had the same structure and coverage but used different numbers.

Test responses were collected and scored only after all students had completed the assessment. The number of correctly solved problems was recorded for each student and aggregated by group. These scores formed the basis for subsequent statistical analysis.

D. Data Analysis and Statistical Methods

To evaluate the effectiveness of the instructional approaches, a combination of descriptive and inferential statistical techniques was employed. The primary outcome measure was the number of correctly solved problems on the post-instruction assessments. These scores were aggregated by group and analyzed to determine whether significant differences existed between the traditional and computer-aided cohorts.

Demographic characteristics of the participants—including gender and school type—were summarized using descriptive statistics. Visual representations in the form of bar charts were used to illustrate group performance and distributional patterns. These visual tools provided an accessible overview of the data and supported interpretation of the results.

To compare group performance, a non-parametric Analysis of Variance (ANOVA) was conducted. Kruskal-Wallis test was selected due to the ordinal nature of the test scores and the potential for non-normal distribution.

The significance threshold was set at $p = 0.01$, ensuring a high level of confidence in the observed differences.

In addition, test scores were categorized into performance intervals to facilitate distributional comparison:

- Grade 5: 0–4, 5–8, 9–12 correct answers
- Grade 6: 0–3, 4–6, 7–10 correct answers.

A Chi-squared test was applied to these intervals to determine whether the score distributions of the traditional and computer-aided groups differed significantly. This approach allowed for a robust comparison of learning outcomes across instructional modalities.

All statistical analyses were conducted after scoring was complete, ensuring that scoring was unbiased and consistent across groups.

E. Ethical Considerations and Timeline

This study was approved by the New Uzbekistan University Ethics Committee (Approval No. F25-1). Informed written consent was obtained from school administrations and from parents or legal guardians of all participants. The purpose and structure of the study were clearly communicated to stakeholders, and participation was voluntary.

To ensure the integrity of the testing process, assessments were administered under strict supervision. High school students were invited to serve as invigilators during all test sessions, minimizing the risk of academic dishonesty and ensuring a controlled environment. Teachers were instructed not to revisit or reinforce the instructional topics during the week following the lesson, preserving the validity of the delayed testing.

All students' data were anonymized to preserve confidentiality. After data were analysed, all students' names were fully erased from all documents.

The instructional sessions and initial assessments were conducted in February 2025. According to the national mathematics curriculum, students received standard instruction on the same topics in late March, without variation in teaching methods across classrooms. To evaluate long-term retention, a follow-up test for Grade 5 students was administered exactly 100 days after the initial lesson. This timeline allowed for a meaningful assessment of both immediate and sustained learning outcomes. All test questions were generated by our software and are not licensed by any third party.

F. Role of the Instructor

Throughout the study, the instructor maintained an active and essential role in guiding student learning, regardless of the instructional format. While the integration of digital tools introduced new modes of engagement, the instructor remained central to content delivery, progress monitoring, and support.

All groups (T5, C5, T6, and C6) began with a structured explanation of the topic delivered by the instructor. This process included verbal explanation, written examples on the whiteboard, and step-by-step demonstrations. This ensured that all students received a consistent foundation before beginning independent practice.

During the practice phase, the instructor monitored student progress using different approaches suited to each setting. In the traditional classroom, this involved reviewing student work in notebooks and engaging in brief one-on-one interactions while some students solved problems on the whiteboard. In the computer-aided groups, the instructor used the software interface to observe student responses in real time. The system highlighted students with frequent errors and displayed their most recent answers, allowing the instructor to identify specific areas of difficulty.

When a student was found to be struggling, the instructor provided targeted assistance. This included revisiting the concept, solving a problem together, and observing the student's approach to subsequent tasks. Such interventions were designed to reinforce correct methods and address misconceptions promptly.

The software's ability to generate a prioritized list of students needing support enhanced the instructor's capacity to deliver timely and focused guidance. This ensured that instructional attention was directed where it was most needed, while allowing other students to continue practicing independently.

IV. Result and Discussion

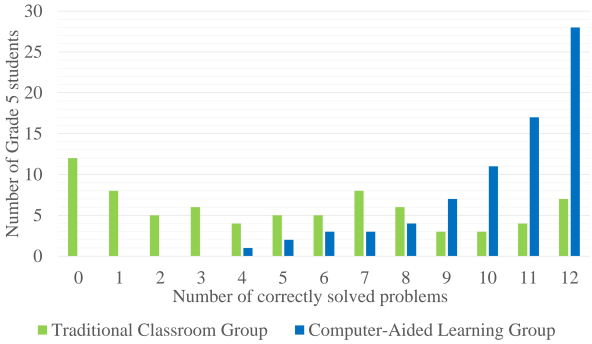
The comparative analysis of student performance revealed a consistent advantage for the computer-aided learning groups across both grade levels. The evaluation considered post-instruction outcomes for both grades as well as long-term retention for Grade 5 students. The study's design ensured consistent content exposure across groups, allowing performance differences to be attributed solely to instructional modality. This methodological rigor aligns with Sung *et al.* [6], which emphasized the importance of controlling for instructional variables in meta-analytic evaluations of mobile-integrated learning.

Fig. 2 shows a similar pattern: the computer-aided group's scores are clustered in the top interval (7–10 correct answers), while the traditional group has a wider spread, with many students scoring below 4.

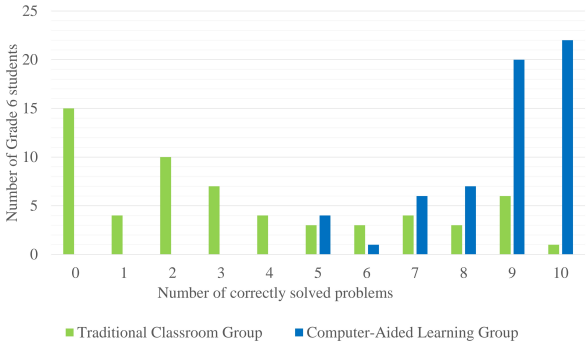
Fig. 2 illustrates the distribution of scores across all groups. The graph demonstrates a clear left-skew in the score distribution for the computer-aided groups, while the traditional groups exhibit a broader spread, with many students scoring in the lower and middle intervals. This pattern signifies a systemic reduction in academic failure and suggests that the immediate feedback and structured digital practice contributed to more effective learning and mastery of the material. These outcomes are consistent with findings of Lashley [2], which showed that elementary students taught via CAI scored significantly higher than those receiving traditional instruction. The results of Tantry and Sofi [3] also reported superior performance among CAI students in a quasi-experimental study, though the sample was limited to secondary education and did not include longitudinal follow-up.

The results of the post-instruction assessments conducted one week after the lesson indicate a substantial difference in performance between the traditional classroom groups and the computer-aided learning groups. Among Grade 5 students, those in the computer-aided group achieved an average score of 85.6% with a standard deviation of 16.8, while the traditional group averaged 43.4% with a broader standard deviation of 33.1. Grade 6 students showed a similar pattern, with the computer-aided group scoring an average of

86.8% and a standard deviation of 15.7, compared to 35% and 31.4, respectively, in the traditional group. These results suggest that the computer-aided method not only improved overall performance but also contributed to greater consistency among students.



(a)



(b)

Fig. 2. Bar chart displaying post-test performance one week after instruction, categorized by the number of correctly solved tasks. (a) Grade 5 students (12 questions); (b) Grade 6 students (10 questions).

Table 1 presents the distribution of correct answers among Grade 5 students, separated by school type and instructional method. In the traditional group, a notable number of students scored in the lowest range, including nine students from the public school who answered zero questions correctly. In contrast, no student in the computer-aided group scored zero. The highest score of twelve correct answers was achieved by twenty-eight students in the computer-aided group, compared to only seven in the traditional group. Table 2 shows similar trends for Grade 6 students, where eleven students from the public school and four from the private school in the traditional group scored zero, while none in the computer-aided group did. The maximum score of ten correct answers was reached by twenty-two students in the computer-aided group, compared to just one in the traditional group. The observed differences between students from public and private schools cannot be interpreted within the scope of this study, as no data were collected on students' socio-economic backgrounds or on the qualifications of their mathematics teachers. The absence of such information reflects its exclusion from the study's original objectives.

Evidence from Mahawan [4] further supports these findings, demonstrating that CAI significantly enhances conceptual understanding in Life Science, suggesting that the benefits of digital instruction extend across disciplines. The present study reinforces this by showing that even a single CAI session can yield substantial gains in mathematics performance.

Table 1. Test results one week after the lesson on rounding decimal numbers for Grade 5 students (12 questions). Results are grouped by school type and instructional method

Number of correctly solved questions	Private School		Public School	
	Traditional	Computer-aided	Traditional	Computer-aided
0	3	0	9	0
1	2	0	6	0
2	2	0	3	0
3	3	0	3	0
4	3	1	1	0
5	4	2	1	0
6	5	2	0	1
7	6	2	2	1
8	6	3	0	1
9	3	6	0	1
10	3	7	0	4
11	4	12	0	5
12	7	16	0	12

Table 2. Test results one week after the lesson on arithmetic operations with integers for Grade 6 students (10 questions). Results are grouped by school type and instructional method

Number of correctly solved questions	Private School		Public School	
	Traditional	Computer-aided	Traditional	Computer-aided
0	4	0	11	0
1	1	0	3	0
2	4	0	6	0
3	6	1	1	0
4	3	0	1	0
5	3	3	0	1
6	2	0	1	0
7	4	5	0	1
8	3	3	0	4
9	6	7	0	13
10	1	18	0	4

Fig. 3 provides a breakdown of performance by gender across three score intervals, highlighting the equalizing potential of the CAL methodology. In Grade 5, twenty-two girls and thirteen boys from the traditional group scored between zero and four, compared to only one girl and no boys in the computer-aided group. In the highest interval of nine to twelve correct answers, sixteen girls and forty-six boys were from the computer-aided group, while only six girls and eleven boys were from the traditional group. For Grade 6, twenty-three girls and thirteen boys in the traditional group scored between zero and three, while only one girl and no boys in the computer-aided group fell into this category. In the top interval of seven to ten correct answers, twenty-five girls and thirty boys were from the computer-aided group, compared to eight girls and six boys in the traditional group. These figures indicate that the computer-aided method benefited both genders, with particularly strong gains among boys in Grade 5 and girls in Grade 6. This suggests that the CAL environment, with its confidential practice setting and instantaneous corrective feedback, serves as a powerful motivational tool. It appears to be effective at overcoming social barriers that often lead to gender disparities in engagement with mathematics, thereby promoting equitable outcomes.

The study by Lee *et al*. [14] explored gender differences in digital learning during COVID-19 and found that competence beliefs and perceived teacher support influenced engagement. The present study's results suggest that CAI may interact with these factors differently across age and gender, indicating a need for further research.

The overall distribution of scores across defined intervals

further confirms the superior performance of the computer-aided groups. In Grade 5, the traditional group had seventeen students in the lowest interval, sixteen in the middle, and eighteen in the highest. The computer-aided group had ten, twelve, and twenty-nine students, respectively. In Grade 6, the traditional group had thirty-six students in the lowest interval, fourteen in the middle, and ten in the highest, while the computer-aided group had one, ten, and forty-nine students, respectively.

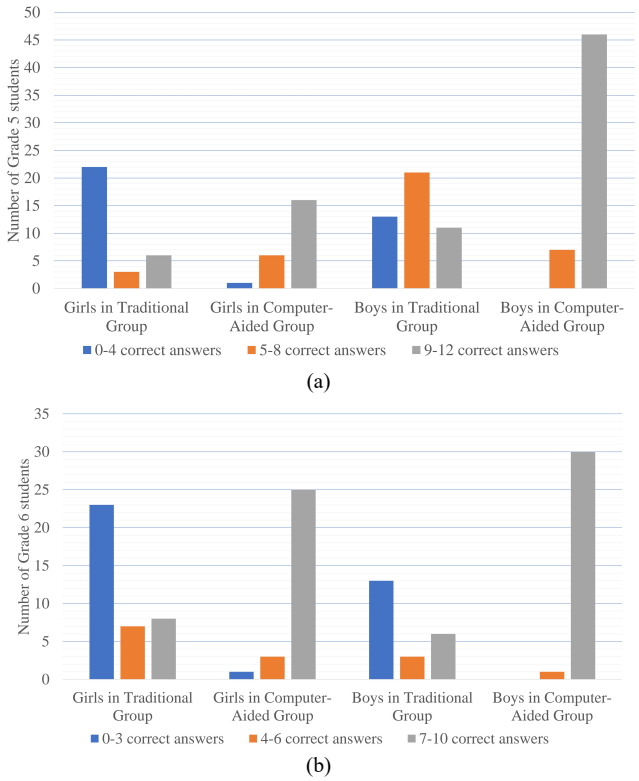


Fig. 3. Distribution of correctly solved tasks by gender and learning groups. Results are grouped into performance intervals. (a) Grade 5: 0–4, 5–8, 9–12 correct answers. (b) Grade 6: 0–3, 4–6, 7–10 correct answers.

To assess retention, a follow-up test was administered to Grade 5 students one hundred days after the initial lesson. Fig. 4 shows that the computer-aided group maintained a higher proportion of students in the top performance band, with twenty-nine students scoring between nine and twelve correct answers, compared to eighteen in the traditional group. The number of students scoring between zero and four was ten in the computer-aided group and seventeen in the traditional group. This suggests that the benefits of computer-aided instruction extended beyond short-term gains and contributed to sustained understanding of the material. Consistent with constructivist theories, this mechanism allows students to immediately correct errors and prevent the consolidation of misconceptions, fostering the active construction of durable knowledge structures. This finding aligns with Kizilcec *et al.* [23], which emphasized the role of feedback-rich environments in promoting durable learning. Similarly, the conclusions of Zhang *et al.* [5] support that adaptive digital instruction enhances retention over time.

The software's real-time feedback and monitoring features enabled instructors to identify struggling students and intervene with targeted support. This dual-layered instructional model—automated feedback coupled with human facilitation—proved effective in enhancing learning outcomes. As shown by Tetzlaff *et al.* [11], personalized feedback significantly improves performance, a principle operationalized in this study's CAI design. The importance of scaffolding in technology-enhanced learning environments was emphasized by Kim *et al.* [21], noting that real-time data allow instructors to tailor interventions. The present study's use of a prioritized list of students needing support exemplifies this approach, demonstrating how CAI can extend teacher capacity without increasing student–teacher ratios.

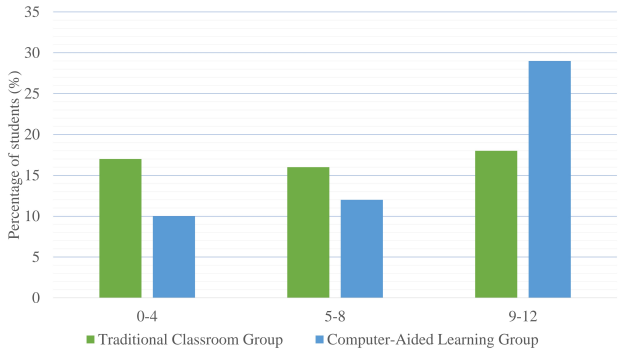


Fig. 4. Distribution of scores on the retention test conducted 100 days after instruction among Grade 5 students. Scores are grouped into three intervals: 0–4, 5–8, and 9–12 correct answers.

A. Statistical Validation

To confirm the observed differences, statistical tests were applied. The non-parametric ANOVA test (Kruskal-Wallis) produced H-statistics of 55.8 for Grade 5 and 61.3 for Grade 6, with *p*-values below 0.0001 in both cases. This test was chosen because Fig. 2 demonstrates clearly a non-normal distribution. The results indicate strong evidence of group differences. The effect size for Grade 5 is 0.37, and 0.52 for Grade 6.

The Chi-squared test applied to the interval-based distributions yielded test statistics of 1201.6 for Grade 5 and 1257.6 for Grade 6, both with *p*-values below 0.0001 and degrees of freedom equal to two. For the Grade 5 follow-up test, the Chi-squared test produced a statistic of 10.41 with a *p*-value of 0.006, also indicating a statistically significant difference in retention between the instructional methods.

The CAL cohort not only maintained higher mean scores but also retained a greater concentration of students in the highest performance interval (29% in the 9–12 range) compared to the traditional group (18%). This robust long-term retention is a direct consequence of the pedagogical features inherent in the CAL environment. Specifically, the system's capacity to deliver immediate feedback for every response prevents the consolidation of errors, enabling students to correct misconceptions instantly and reinforce accurate problem-solving schemas. This process of continuous, targeted course-correction facilitates a deeper and more durable form of learning than delayed, generalized feedback. These outcomes align with the theoretical framework emphasizing that immediate corrective feedback is a critical driver of achievement. Furthermore, our findings reinforce the conclusions of Zhang *et al.* [5], who demonstrated that adaptive digital instruction enhances retention over time, and are consistent with Kizilcec *et al.* [23], who highlighted the role of

feedback-rich environments in promoting durable learning. Therefore, the sustained benefit observed in this study is attributed to the CAL system's effective operationalization of personalized and timely feedback mechanisms, which support the active construction of accurate and long-lasting conceptual understanding.

Table 3 demonstrates the results of other non-parametric tests as well as overall statistics.

Table 3. Summary of group performance and statistical comparison between traditional and computer-aided learning, based on post-test results one week after instruction (mean percentage of correct answers ± standard deviation)

Grade	Traditional	Computer-aided	Statistical tests
Grade 5	43.4% ± 33.1 N = 76	85.6% ± 16.8 N = 76	Kruskal-Wallis = 55.8, $p = 8\times10^{-14}$ Mann-Whitney = 878.5, $p = 3\times10^{-15}$ Wilcoxon = 0, $p = 5\times10^{-13}$
Grade 6	35.0% ± 31.4 N = 60	86.8% ± 15.7 N = 60	Kruskal-Wallis = 61.3, $p = 5\times10^{-15}$ Mann-Whitney U = 324, $p = 10^{-17}$ Wilcoxon = 0, $p = 2\times10^{-11}$

Beyond mean scores, the CAI groups exhibited tighter clustering in the upper performance intervals, while traditional groups showed broader dispersion and a higher concentration of low scores. This pattern suggests that CAI contributes to instructional equity by reducing the incidence of academic failure. Similar distributional effects were observed by Barrow *et al.* [10], which found that CAI not only improved average performance but also accelerated learning pace and reduced variability across student cohorts.

The instructor's role remained central, with digital tools enhancing rather than replacing teacher facilitation. Students in computer-aided groups identified initial instructions as the second most important part of the lesson. The blended learning model advocated by Graham [19] integrates technology with human guidance, a framework reflected in this study's implementation. The software's monitoring interface enabled efficient allocation of instructional attention.

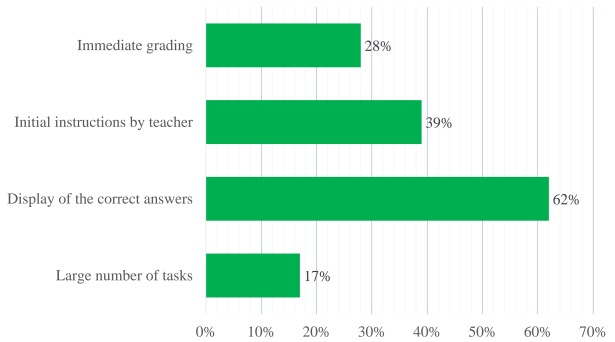


Fig. 5. Survey results indicating which features of CAL students identified as most helpful for understanding the topic and improving academic performance.

Taken together, the results demonstrate that the computer-aided learning approach led to higher and more consistent student performance, both immediately and over time. Fig. 5 presents survey results indicating the student-identified factors that most significantly contributed to their understanding of the topic and academic performance. Display of correct answers was identified as the most influential feature of the software. This provides empirical validation for the effectiveness of the learning model used in the study. The fact that students identified both automated feedback (as the most influential factor) and the teacher's initial instructions (as the second most important factor) confirms that the technology augments—rather than replaces—the essential role of the instructor. This is particularly relevant in the context of teacher shortages, as it highlights the practical utility of CAL as a tool that extends the impact of existing teaching personnel.

B. Limitations of Study

While the findings are compelling, the study's scope is geographically limited to two schools in Tashkent. Although the inclusion of both a public and a private school helped mitigate socioeconomic bias by ensuring representation across differing levels of educational access, the scope of the study remains limited in terms of age diversity and institutional variety.

The instructional intervention focused exclusively on two mathematical topics: rounding of decimal numbers and arithmetic operations with integers. Although these topics represent a narrow segment of the broader mathematics curriculum, they are frequently cited by teachers as areas of persistent difficulty for primary-level learners. The substantial improvement observed in these domains lends weight to the findings and reinforces the pedagogical relevance of computer-aided instruction in addressing foundational mathematical challenges.

The retention test at 100 days was conducted only for Grade 5 students, as almost half of Grade 6 students were absent due to a field trip at that time.

Future research should explore CAI effectiveness across diverse educational settings, including rural and multilingual environments. The benefits of collaborative digital learning in mathematics were highlighted by Safitri [13], suggesting that integrating peer interaction features may further enhance outcomes.

Additionally, the software used in this study did not incorporate adaptive difficulty or gamification elements. Game-based learning strategies aligned with SDG 4 goals have been shown to improve motivation and performance, as demonstrated by Meylani [15]. There remain substantial opportunities for improvement: even within the topics examined in this study, students' response patterns can be used to diagnose the specific sources of their difficulties and to target those misconceptions directly. Incorporating adaptive mechanisms, personalized feedback pathways, and motivational features would therefore allow future versions of the system to provide more precise and effective instructional support, and could extend the pedagogical reach of the CAI system.

V. Conclusion

This study provides strong evidence supporting the effectiveness of computer-aided instruction in enhancing student performance in primary mathematics education. Through a school-based experiment involving 272 students across two grade levels, two mathematical topics, and two school types, the research demonstrated that students exposed to computer-aided learning consistently outperformed their peers in traditional classroom settings.

The integration of automated feedback, individualized pacing, and real-time monitoring contributed to both immediate gains and sustained retention, as confirmed by statistically significant results from non-parametric ANOVA (Kruskal-Wallis) and Chi-squared tests.

The instructional design ensured parity in content exposure across groups, allowing the observed differences to be attributed to the mode of practice rather than instructional bias. The digital platform's capacity to deliver instant feedback and highlight student errors enabled instructors to intervene with precision, reinforcing correct strategies and addressing misconceptions promptly. This synergy between technology and teacher facilitation created a personalized learning environment that traditional methods struggled to replicate.

The findings align with recent international research emphasizing the pedagogical value of automated learning systems, intelligent feedback mechanisms, and data-informed instruction. Studies have consistently shown that technology-supported models foster deeper engagement, improved accuracy, and greater consistency in student outcomes. The present study contributes to this growing body of evidence by demonstrating these effects in a real-world classroom context within Uzbekistan.

The results have practical implications for educational policy and classroom practice. The ability of computer-aided systems to generate large volumes of tailored exercises and provide immediate grading offers a scalable solution to challenges faced by schools with limited teaching staff. In particular, public schools in Uzbekistan, where shortages of qualified mathematics instructors persist, especially in remote areas, may benefit from the adoption of such systems to support differentiated instruction and reduce teacher workload.

While the experiment was conducted in a controlled setting with a limited sample, its outcomes suggest that integrating computer-aided methods into mainstream education can enhance the quality of instruction without altering the student-teacher ratio. The approach is not intended to replace traditional teaching but to complement it, offering tools that extend the teacher's capacity to meet diverse student needs.

Future research should expand the scope of investigation to include larger and more diverse populations, additional subject areas, and longitudinal tracking of academic progress. Exploring the integration of collaborative features, adaptive difficulty levels, and multilingual support may further enhance the effectiveness of computer-aided instruction. As educational technologies continue to evolve, it is essential for educators and policymakers to embrace these innovations and ensure their thoughtful implementation in classrooms.

In conclusion, this study affirms that computer-aided learning, when thoughtfully designed and responsibly integrated, holds significant promise for improving educational outcomes. It offers a pathway toward more equitable, efficient, and responsive teaching practices – one that aligns with the evolving demands of contemporary education.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

AI (the first author) designed the research and provided statistical analysis; SU conducted the research, created the software. All authors read and approved the final manuscript.

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