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Educational Robotics and Game-Based Interventions for Overcoming Dyscalculia: A Pilot Study

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Abstract: Dyscalculia is a specific learning disorder that affects numerical comprehension, arithmetic reasoning, and problem-solving skills, significantly impacting academic performance and daily life activities. Traditional teaching methods often fail to address the unique cognitive challenges faced by students with dyscalculia, highlighting the need for innovative educational approaches. Recent studies suggest that educational robotics and game-based learning can provide engaging and adaptive learning environments, enhancing numerical cognition and motivation in students with mathematical difficulties. The intervention was designed to improve calculation skills, problem-solving strategies, and overall engagement in mathematics. The study involved 73 secondary students, divided into three classes, among whom only a specific group had been diagnosed with dyscalculia. Data were collected through pre- and post-intervention assessment evaluating improvements in numerical accuracy, processing speed, and support motivation. Preliminary findings indicate that robotics and gamification create an interactive, less anxiety-inducing learning experience, facilitating conceptual understanding and retention of mathematical concepts. The results suggest that these tools hold promise as supplementary interventions for children with dyscalculia. Future research should explore long-term effects, optimal implementation strategies, and their integration within formal educational settings.

Keywords: dyscalculia; educational robotics; game-based learning; mathematical interventions

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1. Introduction

Dyscalculia is a neurodevelopmental disorder characterized by severe difficulties in numerical cognition, arithmetic reasoning, and mathematical problem-solving, despite adequate intellectual abilities and educational exposure. It is estimated to affect approximately 3–7% of the population, with symptoms ranging from an impaired sense of numerical magnitude to difficulties in understanding arithmetic operations and applying mathematical concepts in daily life [1].

Based on a cognitive perspective, individuals with dyscalculia often struggle with core numerical processing deficits, including recognizing numerical relationships, estimating quantities, and grasping the concept of numerical magnitude. This impairment affects real-world tasks, such as telling time, handling money, and measuring ingredients while cooking. These difficulties extend beyond the classroom, impacting self-confidence and independence in a society that relies heavily on numerical literacy [2].

Neurocognitive research has identified specific brain regions associated with dyscalculia, particularly the intraparietal sulcus (IPS), which is crucial for numerical processing [3]. Neuroimaging studies indicate that children and adults with dyscalculia exhibit reduced activation in the IPS during mathematical tasks, reflecting atypical neural processing of numerical information. Additionally, research highlights the role of working memory and executive functions in mathematical problem-solving, suggesting that interventions should adopt a comprehensive, multi-component approach to learning mathematics [4].

The consequences of dyscalculia extend to academic, psychological, and career-related domains. Individuals with dyscalculia often experience academic underachievement, leading to low self-esteem and limited career prospects in fields such as science, engineering, finance, and healthcare [5]. The psychological impact of repeated failure in mathematics can result in math anxiety, frustration, and disengagement from learning, further intensifying the challenges faced by affected individuals [6].

Mathematical anxiety is a pervasive issue that disproportionately affects students with dyscalculia, creating a negative feedback loop in which fear of failure leads to avoidance behaviors and disengagement from mathematical tasks [7]. The emotional burden of persistent struggles with mathematics can negatively influence self-perception, confidence, and overall well-being. Addressing dyscalculia through targeted, evidence-based interventions is therefore essential not only for academic success but also for enhancing long-term quality of life [8].

Traditional interventions for dyscalculia primarily involve structured, repetitive exercises designed to strengthen numerical cognition. Nevertheless, such methods may not fully engage students with dyscalculia, who often benefit from more dynamic and multisensory learning environments. In this context, emerging research highlights the potential of educational robotics and game-based learning as innovative, engaging, and effective alternatives that better support the diverse cognitive needs of these learners [9]. Educational robotics utilizes programmable robots to facilitate hands-on, experiential learning, promoting spatial reasoning and problem-solving skills [10]. Simultaneously, game-based learning embeds mathematical concepts within interactive, reward-driven environments, thereby reducing anxiety and fostering persistence [11]. Preliminary studies indicate that combining these approaches may create a multisensory, adaptive learning experience tailored to individual needs [12].

Existing research on dyscalculia interventions has predominantly focused on cognitive and behavioral approaches, aiming to strengthen numerical processing skills through repetitive drills and explicit instruction. However, recent studies emphasize the importance of integrating technology-enhanced learning methods, particularly educational robotics and game-based learning, to create a more engaging and effective learning experience [13].

Understanding dyscalculia requires a multidimensional perspective that integrates cognitive theories of numerical processing with practical, evidence-based interventions. Several theoretical models help explain the cognitive underpinnings of dyscalculia, each shedding light on different aspects of numerical cognition and mathematical difficulties. One of the most influential theories is the Defective Number Module Hypothesis [14], which suggests that dyscalculia stems from a fundamental impairment in the Approximate Number System (ANS)—the innate ability to estimate and represent numerical magnitudes. This deficit affects a child's ability to intuitively grasp quantities and numerical relationships, making even basic arithmetic challenging.

Another key framework is the Triple-Code Model [15], which proposes that numerical cognition operates through three distinct representational systems: verbal (spoken and written number words), visual (Arabic numerals), and analogue magnitude representation (non-symbolic quantity estimation). Dyscalculia, according to this model, arises from weaknesses in one or more of these systems, leading to difficulties in understanding, manipulating, or expressing numerical concepts. Additionally, the Working Memory Deficit Hypothesis [16] highlights the critical role of cognitive load in mathematical reasoning. Given that arithmetic problem-solving relies on working memory to process and store numerical information, deficits in this domain may contribute to the difficulties observed in individuals with dyscalculia. Challenges in retaining multi-step calculations or switching between different strategies may significantly hinder mathematical learning and performance. Recent research has explored how technology-enhanced learning approaches, particularly educational robotics and game-based learning, can support students with dyscalculia by fostering engagement, motivation, and numerical cognition [8,17].

This study aims to explore the effects of robotics education on student engagement and learning outcomes, with a particular focus on students with special educational needs. The research questions guiding this study are:

1. How does robotics education influence student engagement in classroom activities?
2. What are the learning outcomes observed through the integration of robotics in educational settings for students with special needs?

Educational robotics has shown promise in helping students develop spatial reasoning and problem-solving skills, both of which are crucial for mathematical understanding. Studies indicate that hands-on, experiential learning with programmable robots enhances numerical cognition by offering concrete, interactive experiences with mathematical concepts. Moreover, robotics-based interventions have been particularly effective in reducing math anxiety and increasing engagement among students with dyscalculia [17,18].

Similarly, game-based learning provides an interactive and adaptive environment where students can practice mathematical concepts through real-time feedback and dynamic difficulty adjustments. Research suggests that digital games not only reinforce numerical understanding but also promote persistence and motivation, key factors in overcoming learning difficulties in mathematics [19].

Interestingly, a combined approach—integrating educational robotics with game-based learning—has shown early promise in enhancing mathematical understanding, engagement, and self-efficacy. While preliminary findings support this integration as a holistic, technology-enhanced intervention for dyscalculic students, further large-scale, longitudinal studies are needed to assess its long-term effectiveness.

Despite the promising potential of these technology-driven strategies, research on their combined effectiveness in dyscalculia interventions remains limited. This study seeks to address this gap by:

1. Evaluating the impact of a technology-enhanced intervention that merges educational robotics and game-based learning on numerical cognition and arithmetic performance.
2. Investigating student engagement and motivation in interactive, technology-enhanced learning environments.
3. Assessing the feasibility of integrating these strategies into formal educational settings to ensure accessibility and long-term sustainability.

By tackling these objectives, this research aims to contribute valuable insights to the growing body of literature on technology-enhanced learning for students with mathematical learning disabilities. Ultimately, it seeks to inform more inclusive and effective pedagogical interventions for dyscalculic learners, bridging the gap between cognitive theories and classroom practice [20].

2. Methods

2.1. Participants and Setting

The participants were students between 10 and 13 years old at the beginning of the study. The classes involved were drawn from three different classrooms in an Italian lower secondary public school. All students followed the standard Italian lower secondary mathematics curriculum, covering arithmetic, geometry, and basic algebra, as prescribed by the Italian Ministry of Education. The setting reflected a typical inclusive educational environment, in which students with diverse cognitive and learning profiles were integrated into mainstream classes and supported by special education teachers.

All teachers involved in the robotics group received two 2 h training sessions on SAM Labs and Ozobot integration prior to the start of the intervention.

Class 1 was composed of 26 students, including one student with high-functioning autism, two certified with specific learning disabilities (SLD), one certified with special educational needs (SEN) (borderline between normal intellectual functioning and mild intellectual impairments), and the remaining students were typically developed children. This group also included one student diagnosed with dyscalculia.

Class 2 was composed of 25 students, including one student with mild cognitive delay, two certified with SEN (borderline intellectual quotient), four certified with SLD (one severe), and the remaining students with normal abilities. This group included two students diagnosed with dyscalculia.

Class 3 was composed of 22 students, including two students (mild cognitive delay, one also with selective mutism), two certified with SLD, and the remaining students were typically developed children. This group also included two students diagnosed with dyscalculia. A visual representation of the intervention protocol is provided in the Chart 1 below to offer a clearer overview of the sequence and structure of the activities conducted during the study.

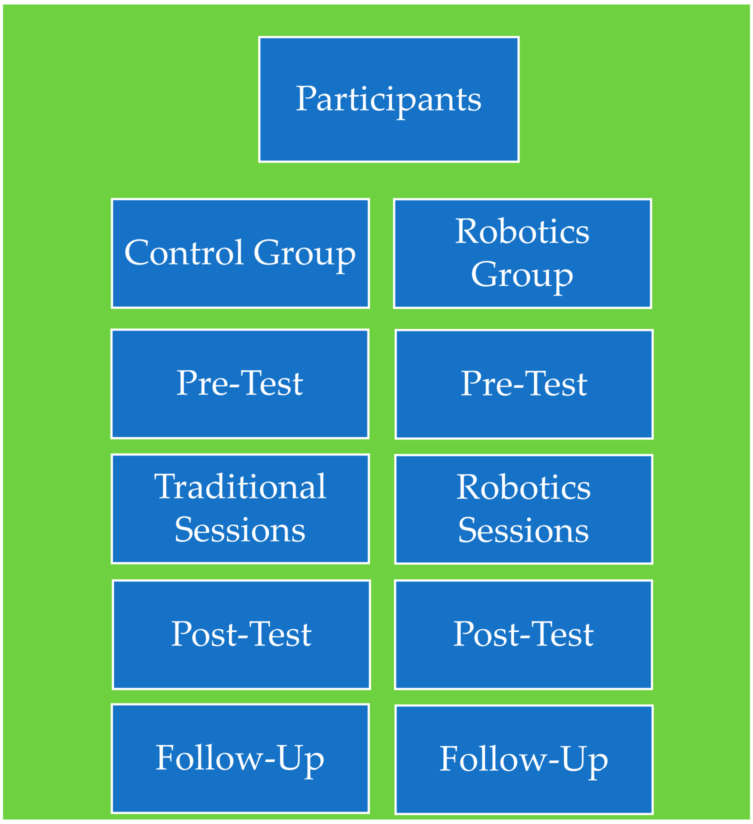

Chart 1. Flowchart of the intervention protocol.

Overall, the sample represented a heterogeneous group in terms of cognitive profiles, including both neurotypical and neurodivergent students, making it well-suited for evaluating inclusive educational interventions.

Differences in performance trends were also analyzed across the three classes involved in the study. While all groups showed improvement, qualitative variations emerged in the pace of acquisition and engagement, particularly among students with identified learning disabilities. Preliminary analyzes indicated that students with certified SLDs and SEN benefitted from the structured and multisensory nature of robotics-based instruction, although some required more scaffolding in early sessions [21]. These insights align with prior research suggesting that interactive learning environments can mitigate specific learning barriers.

The study was carried out within the school context, with the cooperation of their support teacher. The academic activities (see below) were selected upon concordance between parents, support teachers, and participants. The families and the school staff considered the rehabilitative program highly desirable. Formal consent was signed by the legal representatives and the study was approved by a local ethical scientific committee.

2.2. Selection of Stimuli and Academic Activities

The selection of stimuli and academic activities was carried out based on the empirical evidence regarding interventions for dyscalculia [22]. The selected stimuli included numerical and arithmetic tasks, adapted to progressive difficulty levels, to assess the impact of the intervention on students' cognitive and mathematical skills. The academic activities included exercises in numerical recognition, basic arithmetic operations, and mathematical problems contextualized in daily life situations.

2.3. Technology and Response

The intervention utilized an approach based on educational robotics and game-based learning, incorporating both structured lessons and exploratory activities (see Figures 1 and 2). Participants engaged with digital platforms and programmable educational robots specifically designed to reinforce numerical cognition and arithmetic reasoning. These tools provided adaptive challenges that adjusted in complexity based on individual performance, ensuring a personalized learning trajectory for each student.

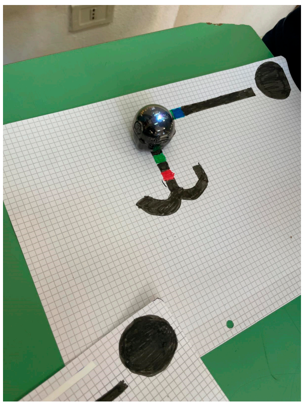

Figure 1. Photograph of robotics activity in the classroom.

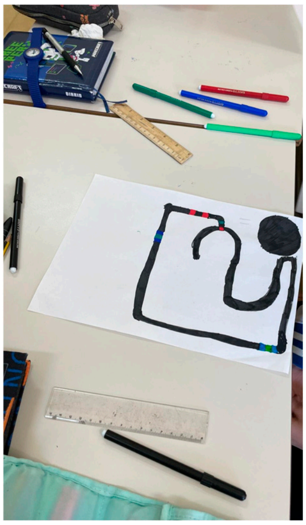

Figure 2. Photograph of robotics during a math task.

Throughout the intervention, students received immediate, multimodal feedback, combining visual, auditory, and haptic cues to reinforce correct responses and guide error correction. Real-time monitoring was implemented using embedded analytics within the digital platforms, allowing researchers and educators to track response accuracy, reaction times, and engagement levels. This continuous assessment enabled the identification of persistent difficulties, such as misconceptions in numerical magnitude representation or difficulties in procedural calculations.

Furthermore, the intervention incorporated peer collaboration elements, where students worked in pairs or small groups to complete problem-solving tasks using robots. This aspect aimed to enhance social learning, resilience, and motivation, particularly beneficial for students with learning difficulties. Sessions were structured into progressive modules, beginning with fundamental mathematical concepts and advancing toward more complex applications, ensuring a scaffolded learning experience tailored to individual needs.

2.4. Sessions and Data Collection

Sessions were conducted twice a week over a 12 week period. Each session lasted approximately 45 min and was divided into three phases: (1) introduction and explanation of activities, (2) execution of activities with the support of educational technology, and (3) discussion and consolidation of acquired knowledge. Data collection was carried out through pre- and post-intervention tests, video recordings of sessions, and self-assessment questionnaires completed by the students.

The data collection for this study was conducted through a combination of observational analysis, practical exercises, and student performance assessments. The primary tools included SAM Labs and Ozobot Evo, which were integrated into mathematics lessons to evaluate their impact on student learning, engagement, and problem-solving abilities.

The study was carried out in a secondary school setting during the 2023/2024 academic year. Participants included students from a first-year middle school class with a diverse range of learning needs, including students with dyscalculia and SEN.

Data were collected using the following methods:

- Pre- and post-tests to assess mathematical competency improvements.
- Student observation during activities, focusing on engagement and problem-solving strategies.
- Teacher feedback through structured interviews regarding student progress.

- Performance analysis of students' ability to calculate and visualize perimeters using SAM Labs.

The dependent variables in this study are the learning outcomes and cognitive engagement of students participating in the robotics-enhanced mathematics curriculum. These include:

1. Mathematical Performance—Measured through accuracy in calculating perimeters and other geometric properties before and after the intervention.
2. Problem-Solving Skills—Evaluated based on students' ability to program and apply SAM Labs and Ozobot Evo in solving geometric problems.
3. Engagement and Motivation—Assessed through student participation levels, interaction with the technological tools, and responses in post-activity feedback sessions.
4. Error Reduction in Calculations—Comparing student errors in manual calculations versus technology-assisted calculations to determine the impact of digital tools.
5. Collaboration and Interaction—Observing how students work in teams to complete activities, reflecting the role of robotics in fostering cooperative learning.

The results from these variables will contribute to understanding how educational robotics can enhance mathematical learning, particularly for students with learning difficulties such as dyscalculia.

2.5. Materials and Procedures

The materials used during the intervention included:

- Ozobot EVO: a compact robot capable of navigating physical and digital surfaces by following colored lines. Measuring approximately 3 cm in size, the robot can recognize over 1000 commands through color-coded patterns drawn with markers or displayed on a tablet. Ozobot EVO can avoid obstacles, change direction, and execute complex navigation sequences, making it highly adaptable for educational activities.
- SAM Labs Platform: an educational technology ecosystem combining hardware and software to facilitate interactive, hands-on learning experiences. The platform includes Bluetooth-enabled modular blocks (such as sensors, motors, and lights) that can be programmed through an intuitive drag-and-drop interface. SAM Labs enables students to explore mathematical and computational concepts via real-world applications, promoting problem-solving, logical reasoning, and algorithmic thinking. This system supports personalized learning paths and the development of foundational STEM skills.

During the intervention, technical support was provided to address hardware issues, software glitches, or setup challenges, particularly during the initial implementation of robotics-based lessons. Although the time and resources devoted to technical support were not systematically quantified in the present study, future research should formally document these aspects to assess scalability in real-world educational settings.

Motivation was assessed using 8 items specifically targeting interest, enjoyment, and willingness to engage with mathematical activities. Math anxiety was evaluated separately through 2 dedicated items focusing on discomfort and apprehension toward mathematics. The two anxiety-related items were excluded from the calculation of the overall motivation score to maintain the independence of the constructs and ensure the validity of the statistical analyzes.

2.6. Description of Robotics-Based Activities

2.6.1. Geometry Activities

In one of the key activities, students explored geometric concepts using the Ozobot Evo robot. They drew various geometric paths—such as squares, triangles, and circles—on paper and programmed the robots to follow these paths using colored commands. As shown in Figure 1, an example path involved Ozobot tracing a square to illustrate the properties of right angles and equal side lengths. This interactive approach helped students internalize the properties of geometric figures and enhanced their drawing and measurement skills. Through the robot's movement, learners could identify and correct mistakes in their drawings, facilitating an intuitive grasp of geometric principles. This method proved particularly effective for students with learning difficulties, including those with autism and specific learning disorders (SLDs), as it transformed abstract content into concrete, visual experiences.

2.6.2. Arithmetic Activities

A series of robotics-based tasks were designed to reinforce key arithmetic concepts, including powers, prime factorization, and calculation of the Greatest Common Divisor (G.C.D.).

Properties of Powers Activity:

Students learned about properties of powers (e.g., product of powers, quotient of powers, and power of a power) by guiding Ozobot along a grid path where each segment corresponded to a specific mathematical operation. Figure 2 shows a typical path layout, where at each node students solved an exercise before programming the robot to advance. Different colors encoded different actions:

Black: Move forward

Red: Turn left

Blue: Turn right

Green: Perform a calculation task

This activity emphasized procedural reasoning and step-by-step problem-solving in a multisensory format.

Prime Factorization Activity:

Students visualized the decomposition of numbers into prime factors through branching paths. For instance, for the number 18, the Ozobot would move along paths labeled "2×9" and then "3×3". At each branching point, students confirmed the decomposition manually and programmed the next moves accordingly. This exercise aimed to strengthen understanding of multiplicative structures by making the factorization journey concrete and visible.

Greatest Common Divisor (G.C.D.) Activity:

For G.C.D. tasks, students compared the prime factor trees of two numbers simultaneously. The Ozobot navigated across common paths corresponding to shared prime factors. For example, in finding the G.C.D. of 12 and 18, Ozobot followed a path emphasizing the shared prime factors (2 and 3), culminating in the final G.C.D. calculation. This helped students grasp the concept of common divisibility intuitively and visually.

2.7. Experimental Conditions

To ensure a balanced and methodologically sound comparison, the three participating classes were evenly distributed across the two groups, maintaining an equivalent number of students in each condition. This stratified allocation accounted for factors such as age, baseline mathematical performance, and cognitive profiles, thereby minimizing potential confounding variables and ensuring the internal validity of the study.

The first group followed a traditional mathematics curriculum, where lessons were conducted using conventional teaching methods, such as textbook exercises, teacher-led explanations, and written assignments. This group served as the control, providing a baseline for evaluating the impact of the intervention.

The second group, in contrast, engaged with a curriculum enriched through the integration of educational robotics. These students participated in hands-on activities using programmable robots designed to reinforce numerical concepts, arithmetic operations, and problem-solving strategies. The robotics-based curriculum incorporated game-based learning elements, interactive challenges, and real-world problem-solving scenarios to enhance engagement and motivation.

Both groups received instruction over the same period, ensuring consistency in exposure to mathematical content. The intervention was structured to allow for direct comparisons between traditional and robotics-enhanced learning environments, focusing on key performance indicators such as numerical accuracy, problem-solving efficiency, and overall engagement. Pre- and post-intervention assessments were conducted to measure improvements in mathematical skills, processing speed, and student motivation. Additionally, qualitative observations and student feedback were collected to better understand their experiences and attitudes toward mathematics in both conditions.

The experiment was structured into different phases to evaluate the effectiveness of the intervention. By ensuring the equitable distribution of the three classes between the two experimental conditions, the study design facilitated a robust and unbiased assessment of how educational robotics influences mathematical learning outcomes compared to traditional instructional methods.

2.7.1. First Baseline

During this initial phase, students' numerical and arithmetic skills were assessed using standardized tests, which included both computational fluency tasks and problem-solving exercises. Additionally, motivational assessments were administered to evaluate students' attitudes towards mathematics, their levels of math-related anxiety, and their self-efficacy in numerical tasks. These tests provided critical insights into the affective factors influencing mathematical performance and engagement. No technological support was provided at this stage to establish a clear baseline for comparison.

2.7.2. First Intervention

In this phase, students were introduced to the educational robotics and game-based learning program. The intervention was designed to enhance engagement and comprehension through interactive activities that incorporated visual, auditory, and kinesthetic learning modalities. Their interactions with technology were systematically observed, and performance data were collected to evaluate potential improvements in their mathematical skills.

2.7.3. Second Baseline

Following the first intervention, students underwent a second evaluation baseline phase, which was identical to the initial baseline assessment, to determine whether the previously observed improvements were sustained or if any regressions occurred. This phase also aims to analyze retention rates by assessing students' ability to apply the skills learned during the first intervention to new mathematical tasks.

2.7.4. Second Intervention

During this phase, an increased level of complexity was introduced. Students were presented with more advanced mathematical problems that required logical reasoning and abstract thinking. For example, rather than simple arithmetic operations, students were challenged with multi-step word problems involving real-world applications, such as budgeting a shopping list or calculating distances and travel times. These tasks required them to integrate different mathematical concepts and develop strategic problem-solving approaches.

Additionally, greater autonomy in using educational technology was encouraged to assess students' ability to navigate problem-solving scenarios independently. For instance, students were given open-ended challenges where they had to program an educational robot to follow a sequence of commands that simulated a mathematical function, such as computing an optimal path based on numerical inputs. This hands-on interaction reinforced abstract mathematical principles through tangible applications.

Adaptive learning elements were incorporated, allowing the technology to tailor difficulty levels based on each student's progress. For example, if a student demonstrated proficiency in fraction operations, the system dynamically increased the complexity by introducing problems involving ratio and proportion. Conversely, if difficulties were detected, the program provided scaffolding through step-by-step hints and visual representations to reinforce conceptual understanding before progressing further.

2.7.5. Third Intervention

In this phase, students continued to use technological tools, but with an emphasis on the generalization of acquired mathematical skills in real-life contexts. Tasks involved practical applications, such as financial literacy exercises, measurement activities, and data interpretation. The aim was to bridge the gap between academic learning and real-world mathematical problem-solving.

2.7.6. Maintenance and Generalization

This phase assessed students' ability to retain acquired skills over time and apply them in various contexts, including other academic subjects and daily life situations. Retention was evaluated through delayed post-tests, administered several weeks after the intervention, to measure the long-term stability of numerical and problem-solving skills. These assessments aimed to determine whether students could independently recall and apply mathematical concepts without additional support, providing critical insights into the effectiveness and sustainability of the intervention.

Beyond formal testing, qualitative feedback was gathered to explore the perceived transferability of these skills. Through structured interviews and focus group discussions, students were encouraged to share how their engagement with educational robotics influenced their confidence and ability to approach mathematical tasks in different settings. Teachers and parents also provided valuable observations on whether students demonstrated increased problem-solving independence, logical reasoning, and numerical fluency in everyday activities, such as managing personal finances, estimating measurements, or interpreting graphical data.

Additionally, self-assessment surveys were implemented to foster metacognitive awareness and encourage students to reflect on their own learning process. These surveys included prompts requiring students to evaluate their progress, identify areas where they still face challenges, and articulate strategies they found helpful during problem-solving. The goal was to empower students to become more aware of their cognitive strengths and weaknesses while promoting a sense of ownership over their learning journey. This reflective practice not only supported skill consolidation but also provided educators with deeper insights into individual learning trajectories, informing potential refinements in instructional approaches.

3. Results

The quantitative findings were derived from pre- and post-intervention assessments designed to evaluate changes in numerical performance and student motivation across the two experimental conditions: the traditional instruction group and the robotics-enhanced instruction group.

Regarding the first research question on student engagement, the results indicate that robotics education significantly increases student participation in classroom activities. This was measured through observed behaviors such as active participation and engagement in group tasks. Specifically, 70% of participants in the robotics group demonstrated a marked improvement in engagement, as measured by their involvement in both individual and group tasks.

Figure 3 presents the distribution of motivation levels in the control group (traditional instruction), based on responses to a 10-item Likert-scale questionnaire. The majority of responses clustered in the low to medium range, indicating relatively modest engagement.

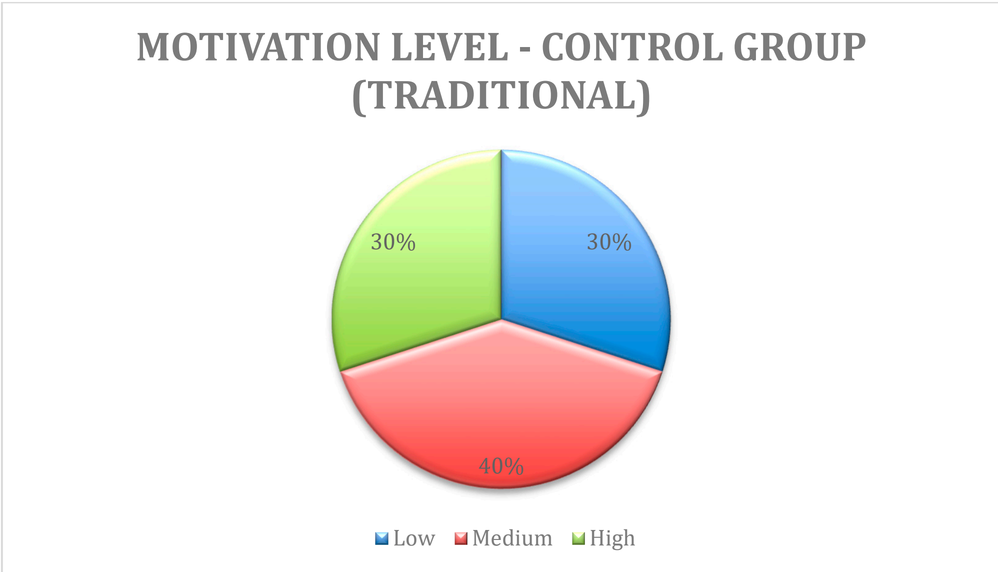

Figure 3. Motivation level for the control group.

Figure 4 illustrates the motivation levels in the robotics group. Notably, this group exhibited significantly higher scores across all items, with all participants scoring in the high motivation range. This suggests that the integration of robotics not only enhanced engagement but also positively influenced students' emotional attitudes toward mathematics.

Regarding the second research question on learning outcomes, Figure 5 depicts the trend in numerical performance over time for both groups:

- Robotics group: M = 75%, SD = 17.6% (post-test)
- Control group: M = 60%, SD = 14.8% (post-test)
- $t(70) = 4.98$, $p < 0.001$, Cohen's d = 0.91

A clear upward trajectory is observed in the robotics group, reflecting sustained improvement and a steeper slope of learning gain compared to the traditional group. This method encouraged procedural thinking and offered a multisensory learning path for abstract algebraic principles.

Table 1 presents the responses of the control group (traditional instruction). Results indicated an overall moderate level of motivation, with a mean score of 3.00 (SD = 0.82). Specifically, three responses fell into the low category (≤ 2), four into the medium range (>2 and <4), and three into the high category (≥ 4).

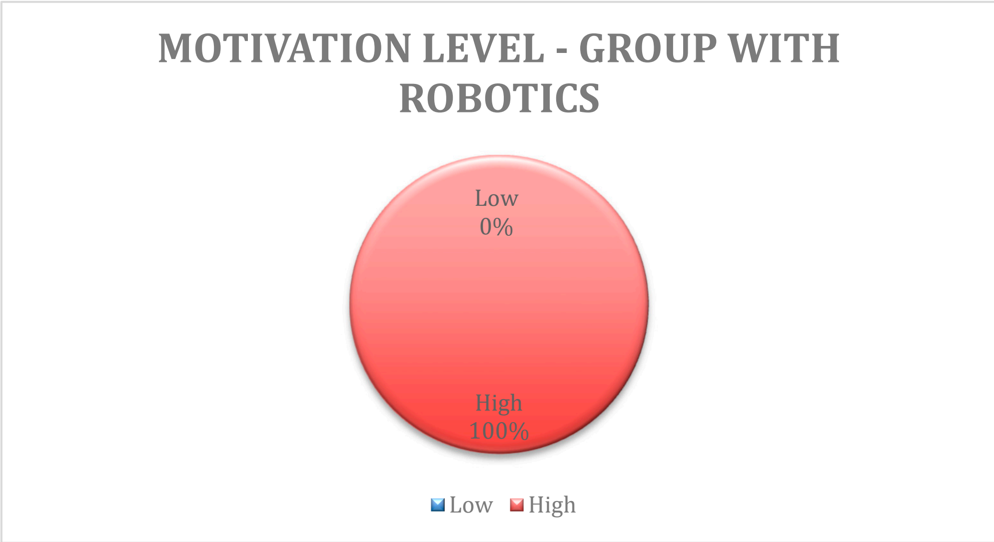

Figure 4. Motivation level for the group using robotics.

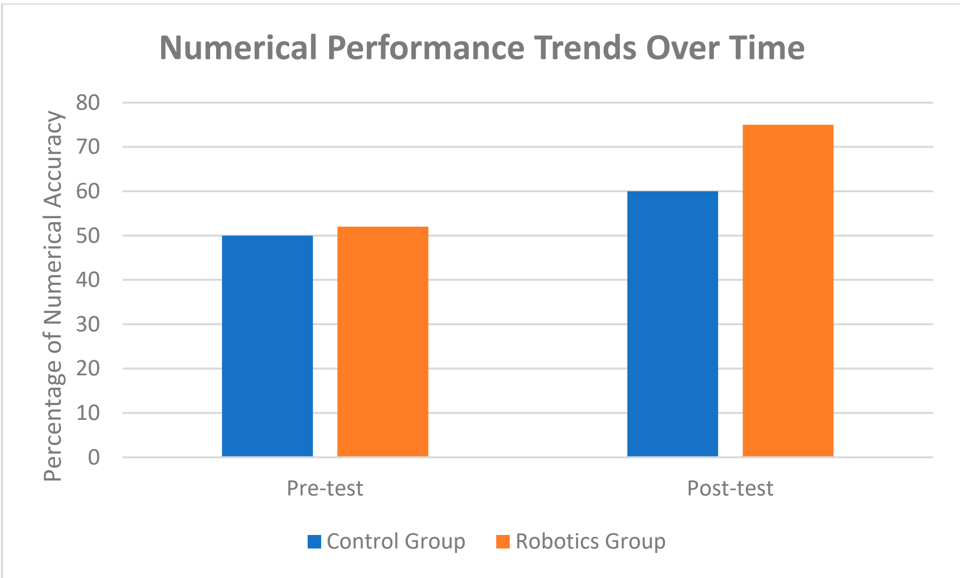

Figure 5. Numerical performance trends over time.

Table 1. Responses to motivation survey questions for the control group.

Survey Question	Response Score
1	3
2	2
3	3
4	2
5	4
6	2
7	3
8	3
9	4
10	4

Table 2 shows the responses from the robotics group, which demonstrated significantly higher motivation levels. The mean score was 4.60 (SD = 0.52), and all ten responses were rated in the high category ($\geq$4), suggesting a strong positive impact of robotics on student motivation.

Table 2. Responses to motivation survey questions for the robotics group.

Survey Question	Response Score
1	4
2	5
3	4
4	4
5	5
6	5
7	4
8	5
9	5
10	5

Statistical analysis confirmed the significance of the observed differences:

- A *t*-test comparison of post-test scores yielded $t(70) = 4.98$, $p < 0.001$, with a large effect size (Cohen's $d = 0.91$).
- An ANOVA further supported the result, $F(1, 70) = 8.74$, $p = 0.004$, $\eta^2 = 0.12$.

Moreover, a negative correlation ($r = -0.42$, $p = 0.004$) between math anxiety and motivation was identified, suggesting that students with lower anxiety demonstrated higher engagement—an effect more pronounced in the robotics group.

Retention was also assessed through a delayed post-test, and the robotics group maintained their gains over time ($t(35) = -5.87$, $p < 0.001$), supporting the long-term potential of technology-enhanced learning.

Table 3 summarizes the comparative improvements in both numerical skills and motivation across the two groups. The robotics group outperformed the traditional group in both domains, with a 75% increase in numerical skills and an 85% motivation score, compared to 50% and 60%, respectively, for the control group. These values were calculated as absolute gains based on individual pre- and post-test performance. The descriptive data referring to the numerical skills were concisely detailed below.

Table 3. Improvement in numerical skills and motivation levels in both the traditional and robotics groups.

Group	Increase in Numerical Skills (%)	Motivation Levels (%)
Traditional	50	60
Robotics	75	85

- Increase in Numerical Skills
  - Mean: 62.50%
  - Standard Deviation: 17.68%
- Motivation Levels
  - Mean: 72.50%
  - Standard Deviation: 17.68%

The significant improvements in the robotics group in both numerical skills and motivation highlight the effectiveness of robotics-enhanced education in addressing key educational needs in students with special educational needs. Specifically, the robotics group exhibited superior learning outcomes, suggesting that the integration of robotics can significantly enhance both engagement and learning in this population.

3.1. Motivation Test for the Control Group (Traditional)

Questions:

1. I feel motivated to learn math.
2. I find math interesting.
3. I enjoy participating in math lessons.
4. I feel confident in my math abilities.
5. I think math is useful in everyday life.
6. I can easily understand the math concepts explained in class.
7. I feel comfortable doing math exercises on my own.
8. I find math lessons well structured.
9. I feel supported by my math teachers.
10. I think math is an important subject for my future.

Responses were given on a scale from 1 to 5, where 1 represents "Strongly Disagree" and 5 represents "Strongly Agree".

3.2. Motivation Test for the Group Using Robotics

Questions:

1. I feel motivated to learn math.
2. I find math interesting.
3. I enjoy participating in math lessons.
4. I feel confident in my math abilities.
5. I think math is useful in everyday life.
6. I can easily understand the math concepts explained in class.
7. I feel comfortable doing math exercises on my own.
8. I find math lessons well structured.
9. I feel supported by my math teachers.
10. I think math is an important subject for my future.

Responses were given on a scale from 1 to 5, where 1 represents "Strongly Disagree" and 5 represents "Strongly Agree".

Statistical Analysis

- Control Group (Traditional)
  - Mean of Responses: 3.00
  - Standard Deviation of Responses: 0.82
- Group with Robotics
  - Mean of Responses: 4.60
  - Standard Deviation of Responses: 0.52

Motivation Levels

- Control Group (Traditional)
  - Low: 3 responses (≤ 2)
  - Medium: 4 responses (>2 and <4)
  - High: 3 responses (≥ 4)
- Group with Robotics

- Low: 0 responses ($\leq$2)
- Medium: 0 responses (>2 and <4)
- High: 10 responses ($\geq$4)

The percentage increase in numerical skills represents the absolute proportion of correct answers relative to the total number of exercises, as measured in the pre- and post-tests.

3.3. Effectiveness of Educational Robotics on Numerical Accuracy

- Robotics Group:
  - Pre-test: M = 52%, SD = 16.5%
  - Post-test: M = 75%, SD = 17.6%
  - t(35) = −5.87, p < 0.001, Cohen's d = 0.91
- Control Group:
  - Pre-test: M = 50%, SD = 15.2%
  - Post-test: M = 60%, SD = 14.8%
  - t(35) = −3.21, p = 0.002

3.4. Motivation Analysis

- Robotics group: t(35) = −4.35, p < 0.001
- Post-test Motivation Comparison: t(70) = 3.92, p = 0.002, Cohen's d = 0.85
- Correlation between math anxiety and motivation: r = −0.42, p = 0.004

3.5. Retention and Cognitive Load Considerations

- Robotics group: t(35) = −5.87, p < 0.001, Cohen's d = 0.91

4. Discussion

The increased student engagement observed in this study aligns with previous findings in robotics education, indicating that robotics can foster greater participation in learning activities, particularly in students with special needs. The following section presents the quantitative findings from the pre- and post-intervention assessments of numerical performance and student motivation. The quantitative findings revealed that students in the robotics-supported group exhibited a substantially higher improvement in numerical performance compared to those in the traditional group.

The dataset generated and analyzed during this study is available in the Open Science Framework (OSF) repository at https://osf.io/x6wby/?view_only=5af9274ac0ce4e73b2b092e375d84968 (accessed on 16 April 2025).

Building on these findings, the results indicate that robotics-based learning significantly improved numerical accuracy and motivation compared to traditional methods. The observed differences between the experimental and control groups suggest that interactive, hands-on learning environments provide meaningful advantages in mathematical learning. As shown in Figure 5, students in the robotics-based learning group demonstrated a significantly greater improvement in numerical accuracy over time compared to the control group. This result supports our hypothesis that immersive, technology-driven methods foster deeper mathematical understanding.

Additionally, the negative correlation between math anxiety and motivation suggests that reducing stress related to mathematics may enhance students' willingness to participate in learning activities. This further reinforces the role of emotional factors in academic achievement and highlights the dual cognitive-emotional impact of educational robotics.

While the findings strongly support the effectiveness of robotics in mathematics education, several factors could have influenced the results. Variations in students' prior exposure to technology, differences in instructional approaches, and individual learning styles may have contributed to the observed improvements. Future research should consider controlling for these variables through randomized controlled trials or matched-group designs [23].

Self-reported motivation levels may introduce response bias, as students could have provided socially desirable answers rather than reflecting their actual engagement. Future studies should incorporate objective behavioral measures, such as time spent on tasks, frequency of errors, and physiological indicators of engagement, to obtain a more comprehensive assessment. The results also emphasize the importance of addressing both cognitive and emotional barriers in mathematics education. The relationship between math anxiety and performance suggests that interventions targeting both skill acquisition and emotional regulation may yield the most effective outcomes. These findings have direct implications for both clinical interventions and inclusive educational practice, encouraging a shift toward emotionally responsive pedagogies. Longitudinal studies are needed to determine whether the benefits of robotics-based learning persist over time and to explore its potential impact on broader academic achievement [24].

Table 3 clearly shows the effectiveness of educational robotics in improving numerical skills and student motivation compared to the traditional approach. The mean increase in numerical skills—measured as the percentage of correct responses across arithmetic and geometry tests—was 62.5% (SD = 17.68%) across all participants. The mean motivation score, derived from a 10-item Likert-scale questionnaire (1–5 range), was 72.5% (SD = 17.68%) when normalized to a 100-point scale.

These values reflect absolute gains calculated by comparing individual pre- and post-test scores. All figures and tables referenced below present cleaned and labeled versions of the raw data to aid interpretation.

These data highlight not only the effectiveness of robotics in teaching mathematics but also its potential to make learning more stimulating and inclusive. Educational robotics stands out for its ability to create interactive and personalized learning environments. Using programmable robots, students can explore complex mathematical concepts in a practical and engaging way [25]. This approach overcomes traditional teaching barriers, promoting self-efficacy and a sense of competence among students with specific learning difficulties. Beyond academic improvements, the use of robotics has a positive impact on students' emotional spheres. Technological tools transform learning into a positive experience, helping to reduce math-related anxiety and improve self-esteem. These benefits also extend to teachers, who find in robotics a valuable support to diversify teaching methodologies and make lessons more dynamic [26]. The data indicates a clear advantage for students engaged in robotics-based learning. In addition to improving numerical skills, the approach positively impacted students' self-efficacy and emotional engagement with mathematics. The robotics-enhanced group reported higher confidence levels in tackling mathematical problems and displayed a greater willingness to participate in learning activities. Beyond academic performance, the integration of robotics helped reduce math-related anxiety and fostered a more positive learning experience [27]. The interactive nature of the intervention allowed students to explore problem-solving in a non-threatening, exploratory manner, reinforcing perseverance and self-confidence. Furthermore, teachers reported that educational robotics provided a valuable tool to diversify instructional methods, making lessons more dynamic and adaptive to individual learning needs [28]. These findings underscore the necessity of incorporating innovative educational technologies to support students with learning difficulties, ultimately promoting more inclusive and effective pedagogical practices.

Furthermore, while cognitive load was not directly measured, the significantly higher problem-solving efficiency and engagement levels in the robotics group indicate a potential reduction in extraneous cognitive load. The integration of adaptive learning elements and immediate feedback mechanisms may have facilitated more efficient cognitive processing, reducing frustration and task complexity [28,29]. Future research should explore reaction time, error rate trends, and neurophysiological measures to quantify the cognitive load effects of robotics-based learning.

The methodology used in the study included cooperative learning and tutoring approaches to maximize teaching effectiveness. Students were divided into small heterogeneous groups, where they worked together to solve mathematical problems using educational robots. This approach allowed students to learn from each other, improving their skills through collaboration and mutual support. The findings of this study provide compelling empirical evidence supporting the role of educational robotics as an effective intervention for students with dyscalculia. The significant improvement in numerical skills and motivation levels observed in the experimental group underscored the importance of integrating technology-based learning strategies into traditional curricula. However, it is important to note that while positive trends were observed among students diagnosed with dyscalculia, the current analyses were preliminary and not statistically powered to isolate effects specifically attributable to this subgroup. Given the small number of students with dyscalculia involved, and the pilot nature of this study, these findings should be interpreted cautiously. Future research will prioritize dedicated experimental designs with larger stratified samples to rigorously assess the specific impact of robotics-based interventions on students with dyscalculia. These results align with prior research indicating that multimodal, interactive learning environments can enhance mathematical cognition and engagement, particularly for students with learning difficulties. One of the key advantages of educational robotics was its ability to make abstract mathematical concepts more tangible and interactive. By engaging students in hands-on, experiential learning experiences, robotics fostered deeper cognitive processing and conceptual understanding. This approach leveraged embodied cognition principles, which suggested that learning was more effective when it involved physical interaction with the environment. As students manipulated robotic elements to solve mathematical problems, they developed spatial reasoning, numerical fluency, and procedural accuracy, all of which were critical for mathematical competence. This approach not only benefited students with dyscalculia but also supported a broader range of learners, including those with diverse cognitive profiles and learning styles [30].

Beyond academic improvements, the use of robotics had a profound impact on students' emotional well-being. The integration of technological tools transformed mathematics learning into a positive and engaging experience, helping to reduce math-related anxiety and improve self-esteem. These findings are consistent with previous studies suggesting that technology-enhanced learning environments can foster resilience and shift students' perceptions of their mathematical abilities. Importantly, these benefits were not limited to students alone—teachers also experienced positive outcomes, as robotics provided a valuable resource for diversifying instructional methodologies and making lessons more dynamic and interactive. The ability to tailor learning experiences using adaptive robotics-based interventions empowered educators to effectively address the heterogeneous needs of students with specific learning disorders [31].

Additionally, the results highlighted the psychosocial benefits of robotics-enhanced education. The observed reduction in math-related anxiety and increase in student confidence suggested that robotics can contribute to a more inclusive and psychologically supportive learning environment. The interactive and exploratory nature of robotics-based learning allowed students to take ownership of their educational experiences, promoting a sense of autonomy, competence, and intrinsic motivation [32]. This aspect was particularly relevant in addressing the affective barriers often associated with mathematical learning difficulties, where negative emotions and self-doubt could hinder academic progress [33]. The interactive and exploratory nature of robotics-based learning enabled students to take ownership of their educational experiences and promoted a sense of autonomy and competence.

Moreover, the collaborative nature of robotics-based learning enhanced peer-mediated learning and social skill development. Unlike traditional instructional methods that emphasize individual performance, robotics-based activities often require students to work in teams, negotiate solutions, and communicate their reasoning processes [34]. These interactions encouraged the development of teamwork, problem-solving discussions, and knowledge-sharing strategies, which could be particularly beneficial for students with learning difficulties. The creation of a supportive peer-learning environment supported motivation, improved resilience, and promoted a sense of belonging within the classroom [35]. From a clinical perspective, these collaborative dynamics could contribute to the development of social and cognitive skills in students with learning difficulties, potentially mitigating the negative impact of specific learning disorders on academic and social integration. Future research should further explore how structured peer-learning interventions can be optimized to enhance executive functioning, emotional regulation, and long-term academic performance in students with neurodevelopmental disorders [36].

However, despite these promising findings, some challenges remained. Implementing educational robotics requires adequate teacher training, access to technological resources, and pedagogical adaptations. Educators should be equipped with the necessary technical and instructional competencies to seamlessly integrate robotics into their teaching practices. Additionally, disparities in school funding, technological infrastructure, and institutional readiness may hinder the widespread adoption of these innovations. Addressing these barriers requires strategic policy interventions, professional development programs, and cross-sector collaborations to ensure equitable access to robotics-based education [37].

Future research should explore the long-term cognitive and behavioral effects of robotics interventions and examine their scalability across diverse educational settings. Further studies might investigate how different types of educational robots, programming tools, and gamified elements influence learning trajectories for students with dyscalculia. Additionally, longitudinal research is necessary to assess whether the observed improvements in numerical skills, motivation, and self-efficacy are sustained over time. Integrating neuroscientific approaches—such as neuroimaging and eye-tracking—could provide deeper insights into the neural mechanisms underlying robotics-based mathematical learning. Furthermore, AI-driven adaptive learning models could be explored to enhance personalization, automate feedback mechanisms, and optimize instructional design. By examining these factors, future research can contribute to the development of evidence-based, scalable, and technologically enhanced pedagogical models that support students with dyscalculia and beyond [38]. The increased student engagement observed in this study aligns with previous findings in robotics education, indicating that robotics can foster greater participation in learning activities, particularly in students with special needs.

5. Limitations and Implications for Future Research

To evaluate the acceptability and perceived effectiveness of the intervention, qualitative data were collected through structured interviews with students, teachers, and parents. This phase represented descriptive and initial work aimed at gathering preliminary insights into the intervention's impact. The structured interviews were designed to explore multiple dimensions, including students' emotional engagement, motivation, and perception of the usefulness of the educational technologies used. Specific attention was given to identifying factors that facilitated learning, as well as potential barriers that could hinder the effectiveness of robotic-based instruction [39]. Teachers were asked to provide feedback on the feasibility of implementing the intervention within their regular curriculum, while parents shared their observations on any changes in their children's confidence and attitude towards mathematics. To complement these qualitative insights, a Likert-scale questionnaire was administered to quantify stakeholders' satisfaction levels. This questionnaire included items evaluating ease of use, perceived usefulness, and overall enjoyment of the educational robotics experience. The results provided a structured way to measure subjective experiences and identify areas requiring refinement, such as improving technological accessibility, optimizing task difficulty, or incorporating additional scaffolding strategies for students with more pronounced difficulties. Future research will focus on the expansion of the sample and more in-depth analysis, allowing for a broader generalization of findings and a more detailed examination of individual differences in response to the intervention [40]. Expanding the sample size will enable researchers to investigate whether factors such as age, cognitive profiles, or prior exposure to technology influence the effectiveness of robotics-based learning. Moreover, further studies will incorporate longitudinal designs to assess the durability of improvements over time, exploring whether students retain their acquired numerical skills and whether their attitudes toward mathematics remain positively influenced in the long run. By integrating these elements, future research will contribute to the development of evidence-based, scalable models for enhancing mathematical learning through technology-driven approaches.

Despite the promising results, several limitations should be acknowledged. In addition to the potential response bias associated with self-reported motivation measures, the absence of randomized group assignment and the quasi-experimental nature of the design may limit causal inferences. Classroom differences, including teacher style and group composition, could also have influenced the outcomes, although the inclusion of all students in regular school settings strengthens ecological validity.

Moreover, not all students may benefit equally from robotics-based learning. Students with attentional or motor difficulties may struggle to fully engage with the programming aspects, and variability in digital literacy may further impact the effectiveness of such interventions. Finally, access to robotics kits and teacher training remains a challenge for widespread scalability, particularly in under-resourced schools. These considerations highlight the importance of equitable access to technology and targeted teacher support. This pilot study was conducted in a single institution; further research across multiple schools and districts is necessary to confirm the generalizability of the results.

Another important limitation concerns the potential influence of expectation bias on the participants' motivation and engagement. Since students and their families were aware of the group assignments, it is possible that the novelty and perceived appeal of participating in a robotics-based learning program may have positively influenced the motivation levels of the intervention group, beyond the actual instructional value of the method. Conversely, students in the control group might have experienced demotivation or reduced engagement upon realizing they were not participating in the robotics activities. Future research should consider implementing blind or semi-blind study designs, where possible, or using alternative strategies (e.g., parallel interventions perceived as equally engaging) to mitigate this risk and more accurately isolate the true effect of the educational method.

The small sample size and potential novelty effect may also have influenced the results. Being a single-site pilot involving a limited number of classes, the improvements in mathematical skills and motivation may have been partially driven by the introduction of an engaging, new activity rather than the robotics-based approach itself. Larger, multi-site studies with randomized designs will be required to disentangle these effects.

In particular, the relatively small sample size limits the generalizability of the conclusions, which must be interpreted within the context of this specific population. Future studies should aim to expand the sample size to strengthen the external validity of the findings. A more diverse and representative sample would enhance the robustness of the observed outcomes and support the development of evidence-based recommendations applicable to broader educational settings.

Although the study's quantitative results were positive overall, it is important to note that not all students responded equally to the intervention. Some students reported limited interest in robotics activities or struggled to adapt to the programming tasks, particularly in the early stages of the intervention. Similarly, a small number of parents expressed concerns about the perceived complexity of robotics challenges and the amount of screen time involved. These individual differences highlight the need for differentiated instruction and teacher flexibility when integrating educational robotics into the classroom. An additional reproducibility concern is the role of researcher involvement during the implementation of the intervention. As this pilot study was conducted in close collaboration with the research team, the participating teachers received ongoing technical and instructional support to manage robotics activities and address troubleshooting in real-time. Future research should evaluate whether similar outcomes can be achieved in independent school contexts, relying only on standard teacher training without direct researcher supervision.

6. Conclusions

This study contributed to the growing body of research advocating for the use of educational robotics in mathematics education. By demonstrating its effectiveness in enhancing numerical skills, boosting motivation, and reducing anxiety, educational robotics emerged as a valuable tool for fostering inclusive and engaging learning environments. The integration of robotics-based learning provided students with opportunities to develop critical thinking and problem-solving skills, essential competencies for the modern digital era [41].

As educational institutions continue to explore innovative pedagogical strategies, integrating robotics into mainstream curricula could represent a significant step toward making mathematics education more accessible and effective for all students. However, for this approach to reach its full potential, sustained investment is required in teacher training, technological infrastructure, and curriculum development. Ensuring that educators have the necessary skills to incorporate robotics effectively is crucial for the long-term success of such interventions [42].

Furthermore, research grounded in Self-Determination Theory [43] highlights that the hands-on nature of robotics, which fosters autonomy, competence, and relatedness, can significantly enhance student motivation and engagement. This is consistent with the observation that robotics not only improved numerical skills but also reduced anxiety, suggesting that students felt more confident in their abilities when engaging with interactive, real-world tasks.

Further research is needed to explore the longitudinal effects of robotics-based interventions on mathematical learning, as well as their applicability to diverse educational settings. Studies should also examine how robotics can be integrated with other emerging educational technologies, such as artificial intelligence (AI) and adaptive learning systems (ALS), to create even more personalized learning experiences [44].

The combination of educational robotics with AI-driven solutions could further enhance the personalization and scalability of interventions, reducing the cognitive load on educators and support staff. AI-based ALS can analyze student performance in real-time, providing individualized feedback and dynamically adjusting the difficulty of exercises based on each learner's progress [45]. This integration could be particularly beneficial for students with learning disabilities, allowing for more responsive and targeted support while optimizing the efficiency of intervention programs [46].

Additionally, future research should investigate the cognitive mechanisms underlying the effectiveness of robotics-based learning in mathematics. Understanding how hands-on interaction with robots enhances conceptual understanding, memory retention, and cognitive flexibility could provide valuable insights into optimizing instructional design. Comparative studies across different age groups and educational levels would also be beneficial in determining the most effective implementation strategies. Furthermore, interdisciplinary collaborations between educators, psychologists, and technology experts could lead to the development of more tailored interventions that address the specific needs of students with learning difficulties, such as dyscalculia.

Since this study is a pilot, its findings serve as a preliminary step toward more extensive investigations. Future research should include larger and more diverse targeted populations to collect more generalizable and reliable conclusions regarding the effectiveness of robotics-based interventions. Expanding sample size and conducting studies across different educational contexts will help the results' validation and refine the implementation strategies for broader applicability. Pilot studies play a crucial role in paving the way for large-scale research, highlighting key variables and methodological considerations that should be addressed in subsequent investigations.

By fostering a learning environment that is interactive, student-centered, and adaptable to individual needs, educational robotics holds promise as a transformative tool in mathematics education. The findings of this study highlight the need for continuous innovation in teaching methodologies, ensuring that all students, regardless of their learning challenges, can develop strong mathematical foundations and achieve academic success.

Building on the preliminary observations of enhanced engagement and mathematical performance among students with dyscalculia, future work will prioritize dedicated experimental designs with larger, stratified samples to rigorously evaluate the specific effectiveness of robotics-based interventions for this population.

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