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TRANSFORMATIVE IMPACT OF ROBOTICS ON STEM EDUCATION: ENHANCING CRITICAL SKILLS IN YOUNG LEARNERS

IMPACTO TRANSFORMADOR DA ROBÓTICA NA EDUCAÇÃO STEM: APRIMORANDO HABILIDADES CRÍTICAS EM JOVENS APRENDIZES

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ABSTRACT

The integration of robotics into education has become a pivotal advancement in enhancing STEM (Science, Technology, Engineering, and Mathematics) learning. This study investigates the potential impact of robotics on educational outcomes by conducting a 10-week intervention involving 60 students, divided into control and experimental groups. The control group followed traditional teaching methods, while the experimental group engaged in hands-on robotics-based learning. Through a combination of assessments and statistical analysis using Student's t-test, the study reveals significant improvements in learning outcomes, student engagement, and perceived satisfaction in the robotics group. Robotics fosters deeper understanding of complex STEM concepts, promotes critical thinking, problem-solving, and teamwork, and enhances student motivation. The findings support the incorporation of robotics into STEM education as a transformative tool for active learning and skill development. Despite the challenges of implementation, robotics offers a promising approach to preparing students for future technological challenges, with implications for reshaping STEM curricula and pedagogical practices.

Keywords: Robotics in Education, STEM Learning, Critical Thinking, Problem-Solving, Hands-On Learning, Educational Innovation.

RESUMO

A integração da robótica na educação tornou-se um avanço fundamental no aprimoramento do aprendizado de STEM (Ciência, Tecnologia, Engenharia e Matemática). Este estudo investiga o possível impacto da robótica nos resultados educacionais por meio de uma intervenção de 10 semanas envolvendo 60 alunos, divididos em grupos de controle e experimental. O grupo de controle seguiu os métodos tradicionais de ensino, enquanto o grupo experimental se envolveu no aprendizado prático baseado em robótica. Por meio de uma combinação de avaliações e análise estatística usando o teste t de Student, o estudo revela melhorias significativas nos resultados da aprendizagem, no envolvimento dos alunos e na satisfação percebida no grupo de robótica. A robótica estimula a compreensão mais profunda de conceitos STEM complexos, promove o pensamento crítico, a solução de problemas e o trabalho em equipe, além de aumentar a motivação dos alunos. As descobertas apoiam a incorporação da robótica na educação STEM como uma ferramenta transformadora para o aprendizado ativo e o desenvolvimento de habilidades. Apesar dos desafios de implementação, a robótica oferece uma abordagem promissora para preparar os alunos para os futuros desafios tecnológicos, com implicações para a reformulação dos currículos STEM e das práticas pedagógicas.

Palavras-chave: Robótica na educação, aprendizado STEM, pensamento crítico, solução de problemas, aprendizado prático, inovação educacional.

Introduction

Educational robotics has become a cornerstone in contemporary teaching methods, enhancing STEM (Science, Technology, Engineering, and Mathematics) education and nurturing vital skills for the 21st century (Jdidou, Aammou, 2023). The integration of robotics into education has emerged as a transformative tool in advancing STEM learning, particularly for young learners. As educational environments continue to evolve in response to technological advancements, the use of robotics has gained traction due to its accessibility, affordability, and capacity to engage students in hands-on learning experiences. More than just a novelty, robotics offers a dynamic approach to education, encouraging the development of critical skills such as problem-solving, critical thinking, and teamwork, all essential in preparing students for future technological challenges.

Traditional methods of teaching STEM subjects often rely on theoretical explanations, which can fail to inspire or fully engage students. In contrast, robotics provides a tangible way to apply abstract concepts (Di Nuovo, Cangelosi, 2021), allowing students to see real-world applications of what they learn in the classroom. The interactive nature of robotics-based activities, such as algorithmic thinking and maze navigation, fosters a deeper understanding of complex ideas while simultaneously cultivating crucial cognitive and collaborative skills. This shift not only enhances comprehension but also sparks creativity and innovation in young minds.

This study seeks to investigate the potential of robotics to improve educational outcomes in STEM subjects by examining a 10-week intervention involving 60 students. Divided into control and experimental groups, participants were tasked with either engaging in traditional learning methods or using robotics to complete various STEM-related tasks. Through rigorous statistical analysis, including Student's t-test, the research explores whether the integration of robotics leads to significant improvements in learning outcomes. The findings contribute to the growing body of evidence supporting robotics as a key educational innovation that promotes deeper learning and skill acquisition in STEM fields.

As the demand for innovative teaching strategies grows, this research aims to highlight how robotics can be effectively integrated into the curriculum to foster a more interactive and engaging learning environment. The implications of this study could reshape the future of STEM education by providing educators with new tools to cultivate the next generation of thinkers and problem-solvers.

1. Theoretical background

1.1. Robotics as a Transformative Tool in STEM Education

Robotics in STEM education enhance cognitive skills, foster interdisciplinary learning, and bridges theory and practice (Zhang et al., 2024), offering students an engaging and interactive way to apply STEM concepts. The accessibility and hands-on nature of robotics make it an attractive tool for educators seeking to enhance learning outcomes. By manipulating robots, students gain an opportunity to see abstract theories in action, fostering critical thinking, creativity, and problem-solving skills essential for technological literacy in the modern world.

1.2. Theoretical Foundations: Constructivism and Experiential Learning

Robotics in education is deeply rooted in constructivist and experiential learning theories. According to constructivist theory, students build their knowledge by interacting with their environment, and Robotics activities align with constructivist learning by encouraging hands-on exploration of STEM principles (Drakatos, Stavridis, 2023). Experiential learning theory complements this by emphasizing the importance of learning through reflection on practical experience. Students working with robotics engage in trial and error, allowing them to understand and refine complex concepts in real-time, which enhances long-term retention and understanding.

1.3. Cognitive Engagement and Skill Development through Robotics

The application of cognitive learning theories in robotics-based education highlights the importance of active engagement in fostering deep learning. Employing robotics in education can enhance cognitive development and skills like computational thinking, spatial relations, and reading ability (Kálózi-Szabó et al., 2022). by offering tasks that involve design, programming, and problem-solving. This active involvement promotes cognitive growth, enabling students to better understand abstract mathematical and scientific principles. Moreover, robotics' ability to increase motivation and engagement has been shown to lead to improved academic performance and a deeper understanding of STEM content.

1.4. Enhancing Collaboration and Interpersonal Skills in STEM Learning

In addition to boosting individual learning outcomes, educational robotics can be used as a tool to develop students' collaboration skills (Demetroulis et al., 2021). Working in teams to complete robotics projects encourages communication, teamwork, and conflict resolution—skills that are crucial for success in the modern workforce. By providing a collaborative, interactive learning environment, robotics-based education prepares students not only for future STEM careers but also for interdisciplinary collaboration in problem-solving contexts, ensuring they are equipped with both technical proficiency and essential interpersonal skills.

1.5. STEM Education and Its Challenges

STEM education is essential for developing critical thinking and problem-solving skills needed in the 21st century technology-driven world (Marzuki et al., 2024), but it faces challenges, including heavy reliance on abstract, theoretical concepts that can disengage students. Additionally, underrepresented groups and limited resources in schools further hinder effective STEM instruction. To bridge these gaps, integrating hands-on, practical learning tools like robotics can make STEM concepts more accessible and engaging, fostering deeper understanding and inclusivity.

2. Methodology

2.1. Participants

Control Group (n=30): Students in this group followed traditional STEM teaching methods, which relied on lectures, textbook-based learning, and theoretical problem-solving tasks. The focus of this approach was to provide a baseline measurement of educational outcomes without the use of robotics, offering a standard comparison for evaluating the impact of robotics-based learning. This group engaged in conventional classroom activities aimed at developing problem-solving and critical thinking skills through non-interactive, traditional methodologies.

Experimental Group (n=30): In contrast, the students in this group utilized educational robotics kits designed to facilitate hands-on learning and interactive problem-solving. These robotics kits allowed students to engage in tasks that required building and programming robots to complete specific STEM-related challenges. The immersive, practical nature of these activities aimed to enhance student engagement and interaction with STEM concepts by promoting algorithmic thinking, teamwork, and creativity. The use of robotics was intended to foster a deeper understanding of STEM principles through experiential learning and dynamic interaction with the course material.

2.2. Procedure

Both groups were enrolled in a meticulously structured 10-week STEM course, designed to maintain consistency in educational content and evaluation methods. This uniformity was crucial to ensure that all participating students were exposed to the same fundamental STEM topics and assessed through identical testing protocols. The course's design was strategic, aiming to isolate the effects of the differing instructional approaches used in each group—traditional teaching methods for the control group versus robotics-based learning for the experimental group—on the learning outcomes. By standardizing the curriculum and assessments, the study ensured that any observed differences in student performance, engagement, or comprehension could confidently be attributed to the instructional method employed, specifically the use of robotics in the experimental group, rather than variations in the educational content itself. This approach facilitated a clear analysis of the impact that hands-on robotics-based learning had on enhancing the educational experience in comparison to traditional teaching methods.

2.3. Data collection

Learning Outcomes: To evaluate the students' comprehension and retention of the STEM material, both groups underwent assessments at the beginning and end of the 10-week course. These pre- and post-tests were designed to quantitatively measure learning outcomes, with scores ranging up to a maximum of 100 points. The tests assessed students' problem-solving abilities, critical thinking, and understanding of key STEM concepts, providing a basis for comparing learning improvements between the control and experimental groups.

Student Engagement: The level of student engagement was measured by observing their active participation in class activities, discussions, and either robotics-based or traditional assignments. Engagement was systematically rated on a numerical scale from 1 to 10, ensuring a standardized evaluation of how actively students participated in the learning process. This method allowed for a comparative analysis of how the two different teaching approaches—traditional versus robotics—affected student interest and involvement in STEM tasks over the 10-week period.

Perceived Satisfaction: To assess students' overall satisfaction with the learning experience, surveys and interviews were conducted at the end of the 10-week course. These tools gathered qualitative feedback on their enjoyment and perceived effectiveness of the instructional methods, whether traditional or robotics based. The results were quantified on a scale from 1 to 10, offering insights into the students' personal evaluations of the course and their satisfaction with the teaching methods and learning outcomes they experienced during the program.

2.4. Hypothesis Testing

H0 (Null Hypothesis): There is no significant difference in learning outcomes, student engagement, and perceived satisfaction between the control group (traditional teaching methods) and the experimental group (robotics-based learning).

H1 (Alternative Hypothesis): There is a significant difference in learning outcomes, student engagement, and perceived satisfaction between the control group (traditional teaching methods) and the experimental group (robotics-based learning).

2.5. Results

Table 1 – Pre-course Test (out of 100)

Group	Mean	SD
Control	55	9
Experimental	50	7

Table 2 – Post-course Test (out of 100)

Group	Mean	SD
Control	64	7
Experimental	78	6

Table 3 – Student Engagement (based on a scale of 1 to 10)

Group	Mean	SD
Control	6.4	1.5
Experimental	8.4	1.2

Table 4 – Perceived Satisfaction (based on a scale of 1 to 10)

Group	Mean	SD
Control	7.5	1.2
Experimental	8.3	0.8

3. Student's t-test

T-tests are statistical tools used to compare the means between two groups. In this study, independent t-tests were performed to examine the effects of two different teaching methods: traditional and robotics-based learning. The analysis focused on learning outcomes, student engagement, and perceived satisfaction in a STEM course. The goal of this analysis was to determine if the differences between the control group (traditional teaching methods) and the experimental group (robotics-based learning) were statistically significant across these key areas.

Independence of Observations: Each student's score was independent and not influenced by the scores of others.

Normality: The distribution of scores for each group was checked to ensure they followed an approximately normal distribution.

Homogeneity of Variances: The variances across the groups were assessed to confirm they were equal.

Using a significance level (alpha) of 0.05:

Learning Outcomes

- T-statistic: 8.32
- p-value: $p < 0.05$

Interpretation: The t-statistic of 8.32 with a p-value less than 0.05 indicates a statistically significant difference in learning outcomes between the control and experimental groups. The experimental group showed significantly improved learning outcomes compared to the control group.

Student Engagement

- T-statistic: 5.70
- p-value: $p < 0.05$

Interpretation: The t-statistic of 5.70 and a p-value less than 0.05 suggest a statistically significant difference in student engagement levels between the two groups. The robotics-based approach significantly increased student engagement.

Perceived Satisfaction

- T-statistic: 3.04
- p-value: $p < 0.05$

Interpretation: The t-statistic of 3.04 with a p-value less than 0.05 indicates a statistically significant difference in perceived satisfaction. Students in the experimental group reported higher satisfaction levels than those in the control group.

The results from the t-tests provide strong evidence that using robotics in the experimental group leads to significant improvements in learning outcomes, student engagement, and overall satisfaction. The hands-on, interactive nature of robotics-based learning clearly outperformed traditional methods in these areas. The notable improvements in learning outcomes, engagement, and satisfaction underscore the value of integrating robotics into the learning process. These findings suggest that expanding the use of robotics in STEM education could foster more engaging and effective learning experiences for students.

4. Discussion: The Impact of Robotics-Based Learning on STEM Education

The findings from this study highlight the significant influence of robotics-based learning on enhancing student performance in STEM subjects. The marked improvement in learning outcomes, student engagement, and perceived satisfaction within the experimental group demonstrates the potential of robotics as an effective educational tool. This section explores the implications of these results, comparing them with previous research, and discusses the benefits and challenges of implementing robotics in educational settings.

4.1. Learning Outcomes: Enhanced Problem-Solving and Critical Thinking

The significant improvement in learning outcomes observed in the experimental group aligns with the growing body of literature emphasizing the effectiveness of experiential learning in promoting deeper understanding of complex concepts. Robotics offers students the opportunity to apply theoretical knowledge in a practical, hands-on manner, thus facilitating better retention and mastery of STEM principles. This reinforces the importance of integrating active learning methods into STEM curricula to promote critical thinking and problem-solving skills.

4.2. Student Engagement: The Role of Interactivity

The higher levels of engagement seen in the robotics-based learning group suggest that interactive and dynamic learning environments capture students' attention more effectively than traditional methods. Robotics activities provide an immersive learning experience, where students are encouraged to collaborate, experiment, and engage directly with the material. This aligns with cognitive theories that support active participation as a key factor in enhancing motivation and improving academic performance.

4.3. Perceived Satisfaction: The Influence of Innovative Tools

The significant increase in student satisfaction within the experimental group highlights the positive impact of innovative teaching tools on the overall learning experience. Students not only found the robotics-based activities more enjoyable but also perceived them as more effective in helping them grasp STEM concepts. This suggests that the use of robotics can lead to more positive student attitudes toward learning, which can further contribute to academic success.

4.4. Challenges and Future Directions

While the study demonstrates clear benefits of robotics-based learning, challenges such as the cost of implementation, teacher training, and curriculum integration need to be addressed. Future research should explore the long-term impact of robotics on student outcomes and investigate how these technologies can be scaled effectively in diverse educational contexts. Furthermore, studies could examine how robotics can be adapted for different age groups or subject areas beyond STEM, potentially broadening the scope of its application in education.

5. Conclusion

This study demonstrates the significant impact of robotics-based learning on improving educational outcomes in STEM subjects. Through a 10-week intervention comparing traditional teaching methods with robotics-based instruction, the findings revealed that students in the experimental group exhibited superior performance in learning outcomes, higher engagement levels, and greater satisfaction with their learning experience. The hands-on, interactive nature of robotics not only enhances comprehension of complex concepts but also fosters critical thinking, problem-solving, and collaboration, all essential skills for future STEM careers.

The positive results from this study underscore the potential of robotics as a transformative educational tool that goes beyond traditional methods, offering a more immersive and engaging approach to learning. However, while the benefits are clear, there are challenges to consider, including the costs of implementation, the need for specialized teacher training, and the adaptation of curriculum to integrate robotics effectively.

As educational institutions continue to evolve in response to technological advancements, the integration of robotics in classrooms can play a pivotal role in equipping students with the skills they need for the future. Future research should explore broader applications of robotics in education and investigate the long-term effects of its use on academic performance and student development across diverse learning environments. The findings from this study provide a strong foundation for further exploration into how robotics can reshape the future of STEM education.

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