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A Critical Review of Educational Robotics and Its Impact on Problem-Solving and STEM Learning

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Abstract: The presented critical review summarises studies conducted under the period of 2020-2026 to examine how educational robotics (ER) affects STEM learning and problem-solving. Based on the constructionist theory and sociocultural theory, ER is a multifaceted medium that bridges the theoretical-practical gap in learning. The literature reveals that ER helps to develop significant computational-thinking skills like sequencing and debugging, and correspondingly increases conceptual understanding in mathematics and science. In addition to technical benefits, ER enhances student motivation, self-efficacy, and interpersonal communication. It also promotes inclusivity amongst neurodivergent learners and under-represented groups. The review also examines how artificial intelligence and social robots can be utilised in conjunction to provide personalised, adaptive learning environments. Despite these strengths, there are barriers to implementation of this educational medium, the most significant of which are outlined in this paper. These barriers include the cognitive-load paradox, the temporality of the novelty effect, and the lack of teacher preparedness. In order to achieve the transformative potential of ER, the authors recommend the implementation of standardised pedagogical models and more rigorous professional development programmes to empower teachers.

Keywords: Educational robotics, social robots, computational thinking, learning-by-teaching, robotics.

INTRODUCTION

Education today is in a paradigm shift whereby the traditional didactic instructional models are giving way to interactive and student-centered models which focus on developing 21st -century competencies. The most important aspect of this change is educational robotics (ER), an interdisciplinary sector, which has become the cornerstone of technological innovation and educational change (Ryalat, M. *et al.*, 2025). ER is not just characterized by the creation of robotic machines but is a complex learning tool that improves the cognitive abilities, leading to synthesis across the disciplines and bridges the long-standing gap in theory and practice that has existed historically (Zhang, D. *et al.*, 2024). Providing students with real objects to think with, robotics outperforms the traditional means of instruction, offering hands-on experiences that allow applying complex scientific and mathematical rules directly.

The economic and industrial need to integrate robotics into the curriculum is huge. The field has also seen convergence between artificial intelligence, materials science and biomechanical systems with a current demand of a workforce skilled in systems thinking and interdisciplinary systems creation with urgency being felt globally (Zhang, X. *et al.*, 2025). According to the global market research, it is estimated that the educational robotics market will grow by USD 1.3 billion in 2021 and around USD 2.6 billion in 2026, with a strong compound annual growth rate (CAGR) of 16.1-28.8 percent (Ryalat, M. *et al.*, 2025). It is not only a commercial expansion, but also an indication of an educational systemic need in which robotics plays a larger and larger role in sectors such as healthcare, manufacturing, agriculture, and autonomous exploration ultimately increasing the need for professionals who possess interdisciplinary expertise in STEM (Chatzichristofis, S. A., & Zinonos, Z. 2023).

Robotics in education is an imperative tool that helps build a full-fledged skill set consisting of technical and necessary soft skills. By integrating the iterative design process, which includes design, testing, and refinement, students can use activities that resemble the scientific method and develop a growth mindset and a sense of resilience when failure occurs (Zhang, D. *et al.*, 2024). This review aims to synthesize the growing body of research from 2020 to 2026, to examine how ER impacts problem-solving capabilities, computational thinking, and achievement across the STEM disciplines. It also challenges conflicting evidence on the novelty effect, cognitive load with physical manipulatives and the socio-educational outlook of equity and inclusion in the digital age.

RESULTS AND FINDINGS

Theoretical Foundations: Constructivism to Social Interaction

The instructional power of ER is largely rooted in the constructionist theory by Seymour Papert, according to which people gain learning power

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most when they construct concrete, exchangeable artefacts (Swenson, A. R. 2023). Constructionism is a development of the constructivism that was developed by Jean Piaget, where the emphasis is laid on the creation of objects to think with (Govender, I. 2025). These artefacts in the robotics classroom serve as reflections of how students think. The physical result gives an external display of the mental logic of the student when he programs a robot to move in a square.

Although constructionism focuses on the engagement of the learner with the artefact, modern robotics pedagogy is adopting more sociocultural theories of Lev Vygotsky. Learning is understood as a social activity, in which children can reach more advanced stages of understanding in the process of collaborative learning with more competent peers or in the process of interactive guidance (Tarakli, I. *et al.*, 2025). Social robots are physical agents with the ability to socialise and interact in the zone of proximal development (ZPD) of a student. They provide a scaffolded support and instant feedback in accordance with the requirements of the specific learner (Tarakli, I. *et al.*, 2025). An example of such a social aspect is the learning-by-teaching (LbT) paradigm. When students demonstrate to a robot what they have learned, thus becoming the tutor instead of the consumer, they need to explain their knowledge in a well-developed manner contributing to the development of a metacognitive focus and an improved learning process in the long run (Tarakli, I. *et al.*, 2025). Experimental research has shown that students with LbT settings will obtain substantially larger retention benefits than students with self-practice, especially on complicated activities that require inference and logical reasoning (Tarakli, I. *et al.*, 2025; Memari, M., & Ruggles, K. 2025). The technological change makes it possible to have a personalised learning experience which can be extended to suit the different classroom settings.

Impact on Computational Thinking and Problem-Solving

The consequences of ER on the development of computational thinking and problem-solving as presented in literature are as follows:

Facets of Computational Thinking in Robotics-Aided Learning

Computational thinking (CT) has been formulated as an important 21st century skill, a skill that is necessary to move in the world that is technologically advanced (Ching, Y.-H., & Hsu, Y.-C. 2023). ER is also the most suitable setting in developing CT, because it requires a translation of abstract algorithms to physical actions (Jordan, S. D. 2023). Empirical studies indicate that robotics interventions are always guided by focusing on several fundamental aspects of CT. These fundamental aspects include are sequencing, conditionals, loops, debugging, and algorithmic thinking (Ching, Y.-H., & Hsu, Y.-C. 2023)

The table below outlines the main aspects of computational thinking as it is operationalised in the context of robotics-based learning,

Table 1: Mapping Computational Thinking (CT) Facets to Robotics-Aided Learning Mechanisms and Target Groups

Computational Thinking Facet	Application Mechanism in Robotics	Primary Target Group
Sequencing	Arranging commands in the correct order to enable robot navigation (e.g., Forward -> Turn -> Stop)	Pre-K to Grade 2
Conditionals	Designing "if-then" logic based on sensor input (e.g., if obstacle detected, then reverse).	Grades 3 to 6
Loops	Creating repeating cycles for efficiency (e.g., repeat the "move and turn" block 4 times to draw a square).	Grades 3 to 6
Debugging	Identifying and correcting errors when the robot's physical behavior deviates from the code.	All levels
Abstraction	Using variables or sub-routines to simplify complex navigation algorithms.	Grades 5 and above

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Robotics have a physicality aspect that presents specialists with their own challenges to CT that are not present in the purely digital world. This claim is exemplified by the fact that it involves a greater degree of critical thinking to diagnose and fix the mistakes in a robot since the learners have to differentiate between bugs in the code, mechanical bugs (e.g. low battery, friction), and environmental bugs (e.g. light variations affecting the sensors). This will require a breakdown of tasks and stringent testing by trial and error *(*Ching, Y.-H., & Hsu, Y.-C. 2023*; Torres, I., & Inga, E. 2025*)

Implications on Analytical and Creative Problem-Solving

Robotics projects generate an active learning environment where students move out of knowing what to the exploration of how and why. Students learn to analyze problems and break them down into smaller tasks that can be solved when they write an algorithm to perform navigation, sorting, or assembling tasks on a large scale (Ching, Y.-H., & Hsu, Y.-C. 2023). It has been shown that in this way, scientific experimentation and inquiry are strengthened since students have to come up with hypotheses and test them in a systematic way by the performance of their robot (Ching, Y.-H., & Hsu, Y.-C. 2023).

Moreover, creative thinking is influenced positively by robotics. Research involving quantitative creativity measures has been able to conclude that students participating in robotics show an improvement in creativity scores (25 percent), especially in the fluency and novelty of their ideas (Zhang, D. *et al.*, 2024). This creativity is encouraged because robotics problems are open ended and each problem has a number of specific solutions. In academia, robotics/games have been demonstrated to aid in the acquisition of intricate programming ideas by minimizing the cognitive load via visualized, task-oriented interfaces (Zamora, P. *et al.*, 2025).

STEM Learning Outcomes

Mathematics: From Abstraction to Visible Action

One of the main issues with mathematical education is that the numbers and formulas may seem abstract, and it may become disengaging. Robotics in education alters this script by turning invisible logic into visible motion (Swenson, A. R. 2023; Frouin, M.-H. 2025). Robots are also used in geometry classrooms as physical pens, drawing precise angles and shapes, transforming a triangular right into an actual three-dimensional object that can be manipulated by hand instead of existing solely as a theoretical construct.

According to empirical studies from UC Davis C-STEM program and other meta analyses, the students in robotics math classes scored up to 12% higher in conceptual understanding evaluations compared to students taught using conventional lecture approaches (Frouin, M.-H. 2025). In students with learning disorders like dyscalculia, interventions based on robotics have been shown to be especially useful in decreasing the levels of math anxiety as well as in enhancing the accuracy of numbers (Stasolla, F. *et al.*, 2025).

Impact on Science and Emgineering

Educational robotics, in the sciences and engineering disciplines, acts as a stimulus to inquiry-based learning and learning the engineering design process. Students learn physics and engineering principles through deep, hands-on learning by creating real-world solutions to problems such as the Bridge Builder Bots that experiment with the structural load distributions (Swenson, A. R. 2023). Robotics applications have been reported to improve science in some fields like the water cycle and the celestial mechanics (Swenson, A. R. 2023).

An example of this improvement is 5th-grade students who made robots to simulate the shape of an ellipsis orbit and showed a much better understanding of the concept of gravitational forces and proportional distance than students who learned the same concept with conventional teaching methods (Memari, M., & Ruggles, K. 2025)]. The iterative nature of robotics design and construction also allows students to engage more effectively in standardised tests as well as develop transversal skills such as teamwork and critical thinking (Zhang, D. *et al.,* 2024; Frouin, M.-H. 2025)

Social and Affective Impacts of Educational Robotics

Teamwork, Motivation and Self-Efficacy

The beneficial effect of educational robotics on student motivation and engagement is an area of constant reporting. Robotics has the inherent prospect of creating a dynamic learning environment that appeals to the youth by its playful and interactive character (Frouin, M.-H. 2025). Students who participate in a learning process based on robotics report increased interest, enjoyment and long-term curiosity towards scientific investigation in surveys conducted

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among students involved in this particular learning style (Ouyang, F., & Xu, W. 2024).

This source of motivation is tightly connected with the enhancement of the self-efficacy- the faith in the ability to reach a particular goal. Students that are able to successfully program robots to complete tasks develop confidence in their technical and problem-solving skills (Govender, I. 2025). Also, robotics projects are largely collaborative as teams are expected to communicate, assign tasks (e.g., coder, builder, data recorder), and integrate various perspectives to reach a project objective. According to studies conducted by peers, students who engage in collaborative robotics project enhance their interpersonal and communication skills by up to 40% (Zhang, D. *et al.,* 2024).

STEM Education Inclusion and Equity

Educational robotics offers a powerful vehicle for fostering inclusion and equity, especially where marginalised settings are concerned or disparate groups of students are underrepresented (Buchem, I. *et al.,* 2025). Programs like the deployment of low-cost, recycled robotic kits in the rural or resource-limited areas have been found to re-involve youth in schooling and rise in enrolment rates (Acosta-Amaya, G. A. *et al.,* 2025).

Robotics, in turn, is a strategic intervention that can enhance the motivation of young girls with regards to their intended major in STEM before society discourages them through its stereotyped notions of women in STEM professions (Voutyrakou, D. A., & Skordoulis, C. 2025). Decade-long longitudinal statistics show that women in robotics programs like FIRST have much higher chances of majoring in either engineering or computer science than their counterparts (Meschede, T. *et al.,* 2024). Nonetheless, these programmes can only be successful when designed inclusively; projects that have a direct impact on the world (e.g., robotics in medicine or education) will be more motivating to girls than solely technical or competition problems (Voutyrakou, D. A., & Skordoulis, C.2025; Meschede, T. *et al.,* 2024).

Robotics for Special Education and Neurodiversity

The non-judgmental and predictable quality of robots makes them especially appropriate with students with a neurodevelopmental and emotional disorder (Symeonidou, E. 2025). Social robots are a kind of controlled environment in which children with autism spectrum disorder (ASD) can practice social skills that help them reduce repetitive behaviours and enhance learning (França, L. F. *et al.,* 2025). Contact with such robots has been identified to reduce feelings of anxiety and increase communication as students report feeling more relaxed when rehearsing social interactions over a structured environment.

In the case of students with attention-deficit/ hyperactivity disorder (ADHD), interactive creativity has been effectively captured by manipulative robotic tasks, which provide a more flexible context in which divergent thinking can be assessed compared with traditional semantic task-based assessments (Kuzmina, O., *et al.,* 2025). Additionally, AI-controlled robots in inclusive classrooms can provide individual tutoring, which can be adjusted to the achievement levels of students in terms of instructional speed and feedback, which is especially helpful when dealing with learners with special educational conditions or learners with migrant backgrounds (Symeonidou, E. 2021)

Technological Advancements: Social Robots and AI Integration

Educational robotics is currently in the process of being redefined by the combination of artificial intelligence (AI) and the spread of social assistance robots (SARS) (Tarakli, I. *et al.,* 2025; Wang, K. 2023) SARS, as it is in the case of the humanoid NAO and Pepper, are designed to interact socially through voice recognition and the synthesis of facial expressions, and thus act as empathetic tutors or peer students (Wang, K. 2023)

This technological evolution allows SARs to transcend their role as static educational aids, functioning instead as empathetic tutors or peer learners that can provide personalized feedback. Through AI-driven adaptivity, these robots can sense a student's emotional state or cognitive load to adjust their instructional pace or social cues to maintain engagement and foster a supportive learning environment (Natarajan et al., 2025). The table below outlines the changing functions of Socially Assistive Robots (SARs) as they shift to active agents in the classroom environment

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Table 2: Pedagogical Roles and Impact of Socially Assistive Robots (SARs) in Educational Settings

Robot Role	Effectiveness and Impact
Co-Teaching	Strong positive effect (d = 0.88) on learning outcomes when assisting a human teacher (de Winter, J. *et al.*, 2025)
Peer Learner	High effectiveness in the "learning-by-teaching" paradigm; enhances meta-cognitive skills (Tarakli, I. *et al.*, 2025)
Social Facilitator	Fosters digital literacy confidence (Memari, M., & Ruggles, K. 2025)]
Adaptive Tutor	AI-integrated systems that manage cognitive load and provide personalized instruction (Buchem, I. *et al.*, 2025)

Recent empirical evidence suggests that the physical nature of social robots results in one of the central determinants of their success. Practical AI creates more interactive and recollect learning experiences than an interaction entirely on a screen. Robots that deliver excitement when a problem is solved or confusion when a student provides an incorrect answer provide nonverbal feedback that reinforces learning (Memari, M., & Ruggles, K. 2025)]. Moreover, the combination of Large Language Models (LLMs) with robotics produces groundbreaking adaptive, learner-centred environments that can support different languages and learning styles (Memari, M., & Ruggles, K. 2025)

DISCUSSION

Critical Gaps and Implementation Barriers

The Cognitive Load Paradox and Physicality

One notable area of conflict in literature is the paradox of the cognitive load of physical robots. Despite the fact that the tangibility of a robot is often contrasted as an advantage, some studies also indicate that it could create an unnecessary amount of extraneous cognitive load, which can subsequently act as a barrier to short-term conceptual learning (Acosta-Amaya, G. A. *et al.*, 2025; Sigayret, K. *et al.*, 2024). When comparing 5th-grade students who used Scratch programming, the students who used Scratch sometimes performed worse than students who used Scratch with a physical robot (Sigayret, K. *et al.*, 2024). The technical nature of learning the robot (e.g. connections, mechanical calibration) may take away the essence of programming and logical decision-making.

The implication of this observation is that whether to use a purely digital environment or a physical robot depends on the desired outcome of instruction. In cases where quick learning of programming syntax is a goal, software might be more effective; however, in the event that the goal is long-term interest and applied context, as well as an interdisciplinary view, robotics can be valuable in a way that software cannot provide (Acosta-Amaya, G. A. *et al.*, 2025). As a result, cognitive load management is to become one of the key elements of educational robotics (ER) instructions design (Gkintoni, E. *et al.*, 2025).

The Novelty Effect and Long-term Learning Retention

A major issue in ER is the novelty effect, which is typified by the increased involvement in the first encounters with new technology (Lee, J. 2025). Intense bursts of motivation can end up fading as technology becomes a routine and robots are reduced to the role of a gadget. Three-week to ten-year longitudinal studies support this phenomenon. While initial novelty can impede learning by causing distractions and cognitive overload, information encoding and exploratory behavior improve as students become more familiar with the virtual or robotic environment (Lee, J. 2025).

Constant practice is the key to the change of novelty to knowledge retention. For example, the FIRST longitudinal study demonstrated that the impact of robotics on STEM interest and career choice remains significantly higher than baseline even ten years after program participation (Lee, J. 2025). This highlights the need to incorporate robotics as part of the long-term curricular frameworks as opposed to the single workshops approach.

Barriers to Teacher Agency and Rea

Successful implementation of educational robotics depends highly on the role played by the educator; however, research has always found teacher preparedness as a key bottleneck (França, L. F. *et al.*, 2025). The challenges include lack of training, insufficient infrastructures and a situation referred

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to as robot anxiety amongst employees. To deal with these problems, research has come up with reliable tools like the TRi-Robotics scale to quantify the pedagogical self-efficacy, commitment, and affective readiness of teachers (Papagiannopoulou, T. *et al.*, 2025).

Professional development programmes should go beyond technical teaching and focus on ways in which teachers can choreograph significant play and enable collaborative learning and project-based learning. Institutional support and the provision of sufficient resources to enable teachers in such transformative roles ultimately determine the success of ER, as it is a sustained process (Impedovo, M. 2025; Sunil, K.P. 2025).

CONCLUSION

This critical review summarizes a wide range of literature suggesting that educational robotics is a transformative tool for improving STEM education and problem-solving skills. Based on constructionist pedagogy, educational robotics creates a distinguished junction between abstract theory and the material world, therefore promoting aspects of computational reasoning like sequencing, logic, and debugging. Besides cognitive advantages, robotics significantly contributes to student motivation, collaboration skills, and self-efficacy, which makes it a powerful means of promoting equity for marginalized populations, reducing gender underrepresentation, and promoting education for neurodivergent learners.

However, the effective integration of robotics requires a nuanced understanding of its challenges. Educators must balance the high motivational value of robots against the potential for extraneous cognitive load and manage the transition from the initial novelty effect to long-term knowledge retention. The teacher role cannot be substituted; robotics should also be placed as a supportive supplement to human training instead of a replacement factor. Further studies and policy making must focus on the invention of systematic didactic models, the improvement of teacher professional growth, and the investigation of the overall potential of AI-integrated social robots to establish adaptive and inclusive learning environments in the 21st century.

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