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Educational Robotics in K–12 Education: Applications, Benefits, Challenges, and the Human–Robot Partnership Model

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ABSTRACT
The rapid development of robotics and artificial intelligence (AI) is creating new possibilities for teaching and learning across Kindergarten through Grade 12 (K–12) education. This review examines the role and educational applications of robotics in K–12 settings, with particular attention to STEM education, programming and computational thinking, mathematics, language learning, personalized learning, social and emotional learning, early childhood education, and special and inclusive education. The reviewed literature indicates that educational robots can serve as tutors, teaching assistants, learning companions, demonstrators, programming platforms, and collaborative learning partners. Evidence from recent systematic reviews and meta-analyses suggests that educational robotics can produce positive effects on students' learning outcomes, STEM learning, engagement, problem-solving, collaboration, and technological competencies. However, these benefits vary according to instructional design, educational context, comparison conditions, and the nature and duration of robotic interventions. The review also identifies important challenges, including cost, infrastructure requirements, teacher preparation, technical reliability, privacy and data protection, ethical concerns, accessibility, and potential distraction or cognitive load. Importantly, existing evidence does not establish that robots are superior to human teachers or that they can replace the broader pedagogical, social, emotional, and contextual functions of teachers. The review therefore supports a human–robot partnership model in which robotics complements rather than replaces human teaching. Effective implementation requires curriculum alignment, teacher involvement, adequate infrastructure, ethical safeguards, and rigorous evaluation of educational outcomes.
Keywords: educational robotics; K–12 education; robot teacher; artificial intelligence; STEM education; social robots; personalized learning; human–robot interaction

1. INTRODUCTION

Technological developments have increasingly influenced educational practice, particularly through artificial intelligence, digital learning environments, automation, and robotics. Educational robotics refers broadly to the use of robots and robotic technologies to facilitate teaching and learning. In K–12 education, robots can be used not only as objects of study but also as instructional tools, learning companions, tutors, and classroom assistants. The use of robotics in education has developed substantially over the past two decades. Early educational robotics research emphasized programming, construction,

engineering, and STEM learning, whereas more recent work has expanded toward socially interactive robots capable of communicating with learners through speech, movement, gestures, and other social behaviors (Belpaeme et al., 2018). Systematic reviews have identified applications across STEM education, language learning, early childhood education, special education, and social learning (Benitti, 2012; Toh et al., 2016).

The idea of a "robot teacher" nevertheless requires conceptual clarification. A robot may deliver information, ask questions, provide feedback, demonstrate a process, or guide a learner through an activity, but teaching involves substantially more than information delivery. Human teachers interpret learners' needs, develop relationships, manage classrooms, make contextual judgments, provide emotional support, and adapt instruction to unexpected circumstances. Consequently, robotics should generally be viewed as a technology for augmenting teaching rather than as a straightforward replacement for teachers.

Recent evidence provides a more nuanced picture. Wang et al. (2023) synthesized 34 effect sizes from 17 studies and reported a moderate positive effect of educational robots on learning outcomes. Similarly, Ouyang and Xu (2024) found a moderate positive effect of educational robotics on STEM learning across 21 studies. More recently, Lu and Geng (2026) synthesized 108 effect sizes from 58 studies involving 5,806 learners and reported a moderate-to-large overall effect of educational robotics on learning outcomes. However, these findings should not be interpreted as evidence that robots can replace teachers, because the interventions and comparison conditions varied substantially across studies.

2. Conceptualizing Robotics as a Teacher

Educational robots can perform several roles within K–12 education. Belpaeme et al. (2018) identified social robots as potential tutors and peer learners and emphasized the importance of their physical embodiment in educational interaction. Unlike purely screen-based technologies, robots occupy a physical space and can interact with learners through movement, speech, gestures, and other embodied behaviors. Within K–12 education, robotic systems can function as: Tutors, providing explanations, questions, demonstrations, and practice; Teaching assistants, supporting repetitive instructional activities; Learning companions, encouraging learners and participating in educational activities; Demonstrators, physically illustrating scientific and mathematical concepts; Programming platforms, through which students learn coding and computational thinking; and Collaborative partners, participating in problem-solving and project-based learning.

The distinction between a robot being a "teacher" and a robot being a "teaching tool" is therefore important. In most educational contexts, the teacher remains responsible for establishing learning objectives, selecting instructional strategies, interpreting student performance, and making educational decisions.

3. Applications of Robotics in K–12 Education

3.1 STEM Education

STEM education is one of the most prominent applications of educational robotics. Robots provide students with opportunities to integrate science, technology, engineering, and mathematics through practical activities. Students can design, construct, program, test, and modify robotic systems while applying theoretical knowledge to real-world problems.

A systematic review by Benitti (2012) found evidence that robotics can contribute to learning, particularly in STEM-related areas, although positive effects were not universal. More recent research has strengthened the evidence base. Ouyang and Xu (2024), in a multilevel meta-analysis of 21 studies and 30 effect sizes, found a statistically significant moderate effect of educational robotics on STEM learning. ([ScienceDirect. Robotics-based STEM education can also encourage inquiry and engineering design. Students may be required to identify a problem, develop a solution, construct a prototype, test it, identify errors, and redesign the system. This process closely resembles authentic engineering practice.

3.2 Programming and Computational Thinking

Robotics provides a physical context for learning programming. Rather than seeing programming only as abstract commands on a computer screen, students can observe their code producing physical actions.

Young learners can use visual programming environments to develop concepts such as sequencing, loops, conditions, and debugging. Older students can progress to text-based programming, sensors, algorithms, autonomous navigation, and AI.

However, the relationship between robotics and computational thinking is not automatically positive. Ouyang and Xu (2024) found that while educational robotics produced moderate effects on STEM learning overall, its effect on computational thinking was not statistically significant in their analysis. This finding suggests that simply using robots does not guarantee computational-thinking development; activities must be deliberately designed around appropriate computational-thinking objectives.

3.3 Mathematics Education

Robotics can provide concrete representations of mathematical concepts. Students can use robots to investigate distance, speed, angles, measurement, geometry, coordinates, ratios, and patterns. For younger learners, robot-based activities can make mathematical concepts more tangible. Instead of learning measurement solely through worksheets, for example, students can program a robot to travel a specified distance and compare predicted and actual movement. The effectiveness of such activities depends on the instructional design and the extent to which students focus on the mathematical concept rather than merely operating the robot.

3.4 Language Learning

Social robots have also been investigated as tools for language education. Robots can conduct structured conversations, introduce vocabulary, ask questions, provide pronunciation practice, and participate in storytelling activities. A review by van den Berghe et al. (2019) reported growing interest in social robots for language learning and identified potential benefits associated with interaction, engagement, and individualized practice. One potential advantage is repetition. A robot can repeat vocabulary or conversation exercises many times without fatigue. Nevertheless, human interaction remains important because language learning involves culture, pragmatics, emotional interpretation, creativity, and communication in unpredictable contexts.

3.5 Personalized Learning

Robotics combined with AI may support personalized learning by adjusting activities to individual learners. A robotic system could potentially provide additional practice when a learner experiences difficulty or increase task complexity when performance improves. However, personalization should not be confused with simple adaptation. Effective personalized learning requires reliable assessment, appropriate educational content, accurate interpretation of learner performance, and pedagogically appropriate responses.

Therefore, teachers should remain involved in interpreting robotic feedback and deciding how it should influence subsequent instruction.

3.6 Social and Emotional Learning

Social robots are designed to communicate using human-like social behaviors such as speech, gestures, gaze, and movement. These characteristics have led researchers to investigate their use in social and emotional learning. Belpaeme et al. (2018) found that social robots can influence cognitive and affective outcomes in certain educational tasks. However, the authors also emphasized technical and interaction-related challenges. Robots may therefore provide opportunities for structured social activities, but they should not be assumed to possess human emotions or genuine empathy. Their apparent emotional responses are generated by programmed or AI-mediated behavior.

3.7 Early Childhood Education

Robotics has particular potential in early childhood education because young children often respond positively to physical, interactive learning objects. Toh et al. (2016) reviewed research involving robots and young children and identified applications involving educational activities, children's behavior, stakeholder perceptions, and robot appearance. Research on robotics education for young children also indicates the importance of constructivist and constructionist approaches, in which children actively manipulate and create rather than simply receive information from technology. (Kim et al., 2018). For

Kindergarten and early primary education, simple robots may therefore be particularly useful for sequencing, storytelling, movement, pattern recognition, basic coding, and introductory problem-solving.

3.8 Special and Inclusive Education

Robotic technologies have also been investigated in special education. Social robots can provide predictable, repeatable interactions and structured learning activities for some learners with disabilities. A systematic review by Dautenhahn et al. and subsequent research in social robotics indicates potential applications in autism-related interventions and communication support. However, the evidence varies according to the population, intervention design, duration, and learning outcome. Robotics should therefore be regarded as a supplementary educational resource rather than a universal intervention for learners with special educational needs.

4. Educational Benefits of Robotics

4.1 Student Engagement

The physical presence and interactive behavior of robots may increase learners' interest and participation. Students can manipulate robots, observe their responses, and experiment with different solutions. However, engagement should not be equated automatically with learning. A robot may attract considerable attention without producing meaningful learning if the activity is poorly designed.

4.2 Immediate Feedback

Robots can provide rapid feedback. For example, when students program a robot incorrectly, the robot may fail to perform the intended action. Students can then identify the problem and modify their program. This creates a cycle of experimentation, feedback, debugging, and revision.

4.3 Problem-Solving

Robotics activities often involve open-ended problems that require learners to analyze situations, develop solutions, test alternatives, and revise their designs. Such activities can support higher-order thinking when teachers explicitly encourage students to explain their reasoning rather than simply complete a technical task.

4.4 Collaboration

Many robotics projects are conducted in teams. Students may divide responsibilities among programming, construction, testing, documentation, and presentation. Research on robotics-based STEM education has consequently emphasized its potential to support interdisciplinary and collaborative learning (Darmawansah et al., 2023). Their systematic review of robotics-based STEM research found that a substantial proportion of the literature focused on K–12 education.

4.5 Learning Outcomes

Recent meta-analytic evidence provides support for educational benefits. Wang et al. (2023) found a moderate positive overall effect of educational robots on learning outcomes ($g = 0.57$). Ouyang and Xu (2024) reported a moderate positive effect on STEM learning (Hedges' $g = 0.488$). A 2026 three-level meta-analysis by Lu and Geng synthesized 108 effect sizes from 58 studies involving 5,806 students and reported an overall effect of $g = 0.756$. The authors also reported positive effects for both cognitive and affective outcomes. However, the analysis found that the comparison condition mattered: the relative advantage of robotics was larger when compared with traditional instruction than when compared with other technologies. These findings suggest that educational robotics has measurable potential but that its effectiveness depends on how it is implemented and what it is compared against.

5. Challenges and Limitations

5.1 Cost

Robotic equipment can be expensive. Costs may include hardware, computers, software, batteries, replacement parts, maintenance, and teacher training. A recent review of low-cost social robots identified affordability as an important barrier to large-scale adoption, particularly because many studies remain limited to short-term or laboratory-based interventions (Rutatola et al., 2026).

5.2 Infrastructure

Effective robotics programs may require reliable electricity, computers, internet connectivity, suitable classroom space, and technical support. In low-resource educational environments, infrastructure limitations can restrict the sustainability of robotics initiatives. Schools should therefore consider locally appropriate and maintainable technologies rather than relying exclusively on sophisticated commercial systems.

5.3 Teacher Preparation

Teachers require adequate professional development to use robotics effectively. Technical training alone is insufficient; teachers must also understand how robotics can support curriculum objectives. Professional development should include: basic robot operation; programming; troubleshooting; lesson design; classroom management; assessment; AI literacy; and ethical and privacy considerations.

5.4 Technical Reliability

Robots can malfunction, lose network connectivity, misunderstand speech, or respond incorrectly. These problems can interrupt lessons and reduce instructional time. Field-based research highlights the difficulty of achieving long-term autonomous interaction between robots and children in real classrooms (Woo et al., 2021). Their review of 23 classroom studies found that research had demonstrated feasibility but had not established that social robots were more effective than human teachers or other educational technologies.

5.5 Privacy and Data Protection

AI-enabled robots may collect voice recordings, student responses, behavioral information, or learning data. Such information can be sensitive when the users are children. Schools should therefore establish clear policies governing data collection, storage, access, retention, consent, and deletion. Data minimization and strong security should be central principles of implementation.

5.6 Ethical Issues

The use of robots with children raises ethical questions concerning autonomy, attachment, deception, privacy, safety, bias, and accountability. A robot designed to appear emotionally responsive may lead children to attribute human-like characteristics to it. Educational institutions should therefore ensure that children understand the nature and limitations of robotic systems. Ethical considerations are especially important in early childhood environments, where children's understanding of artificial agents is still developing.

5.7 Cognitive Load and Distraction

Robots can sometimes distract students from the educational objective. The physical novelty and complexity of the technology may consume students' attention that should be directed toward the subject matter. Research has documented cases in which robotics did not improve learning and, under certain conditions, could introduce additional cognitive demands (Ouyang & Xu, 2024). Consequently, the educational objective should always determine the use of the robot, rather than the novelty of the robot determining the lesson.

6. Robotics Versus Human Teachers

The question of whether robots can replace teachers should be approached cautiously.

Dimension	Educational robots	Human teachers
Repetitive practice	High potential	Possible but time-consuming
Programmed feedback	High potential	High potential
Physical demonstrations	High potential	High
Data-based adaptation	Increasing potential	High with appropriate tools
Emotional understanding	Limited	Strong
Classroom judgment	Limited	Strong
Relationship building	Limited	Strong
Handling unexpected situations	Limited	Strong
Moral and contextual judgment	Limited	Strong
Creativity	Developing but limited	Strong
Mentoring	Limited	Strong
Programming education	Useful learning platform	Provides pedagogical guidance

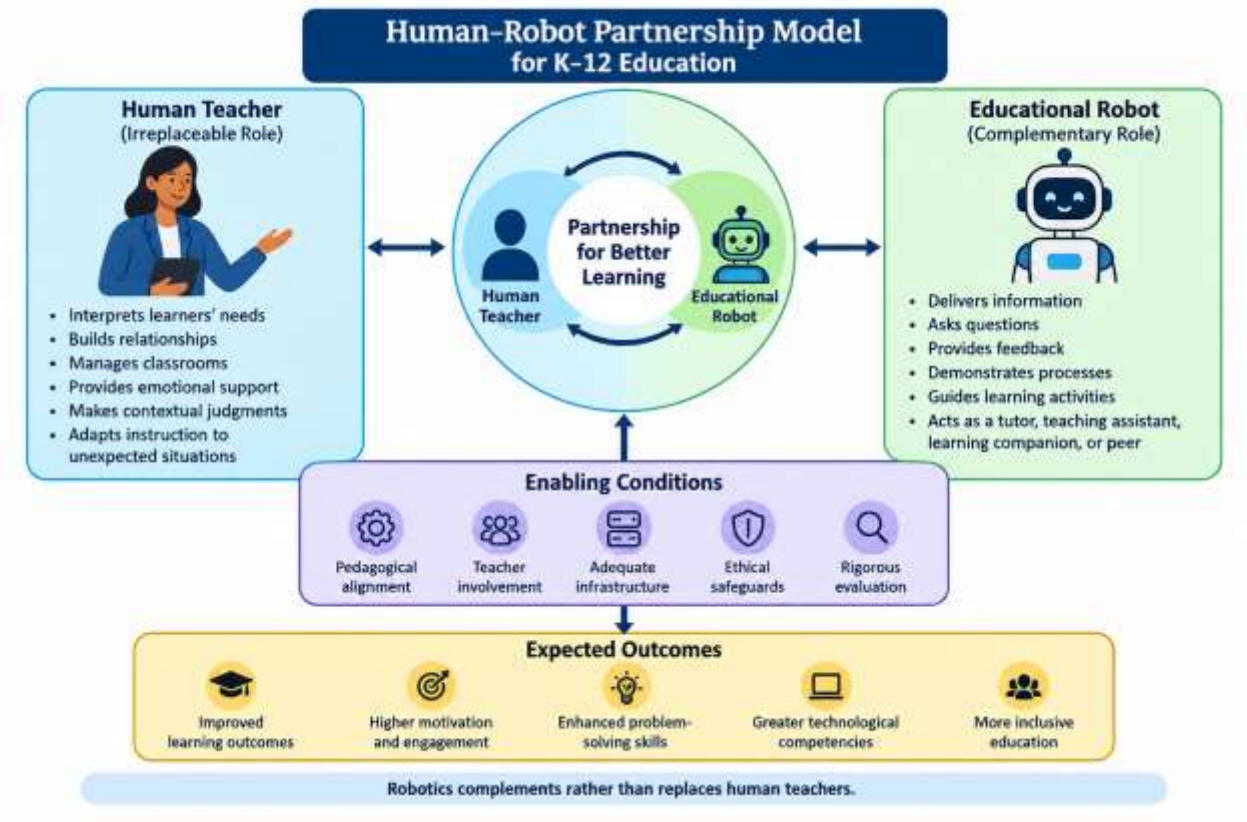
Social-robot research has not established that robots are superior to human teachers in classroom learning (Woo et al., 2021). The evidence instead supports a complementary model. Robots can perform particular functions efficiently, while teachers provide the broader educational, social, emotional, and contextual framework.

7. The Human–Robot Partnership Model

A more realistic model for K–12 education is the human–robot partnership model. In this approach, the teacher remains the central educational decision-maker while the robot performs selected supporting functions. For example, during a mathematics lesson:

1. The teacher introduces the mathematical concept.
2. The robot demonstrates a practical example.
3. Students work in small groups to program the robot.
4. The robot provides immediate feedback.
5. The teacher observes student reasoning and misconceptions.
6. Students explain their solutions.
7. The teacher conducts assessment and provides individualized guidance.

This model uses robotics where its physical and computational capabilities provide educational value while retaining the strengths of human teaching.



The Human–Robot Partnership Model for K–12 Education illustrates how human teachers and educational robots can work together to enhance teaching and learning. The human teacher remains the central educational decision-maker**,** responsible for understanding learners' needs, building relationships, managing the classroom, providing emotional support, and making contextual pedagogical decisions. The educational robot serves a complementary role, supporting activities such as demonstrating concepts, asking questions, providing immediate feedback, guiding learning activities, and facilitating practice and programming tasks. The model therefore emphasizes augmentation rather than replacement of teachers. Its effectiveness depends on enabling conditions such as pedagogical alignment, teacher involvement,

adequate infrastructure, ethical safeguards, and appropriate evaluation. Overall, the diagram shows that combining the unique strengths of teachers with the interactive and computational capabilities of robots can support improved learning outcomes, engagement, problem-solving, technological competencies, and inclusive education.

8. Pedagogical Considerations

Robotics should be introduced according to learning objectives rather than technological novelty.

A well-designed robotics lesson should answer three questions:

First, what should students learn? The learning objective should be clearly defined before selecting a robotic activity.

Second, how does the robot contribute to that objective? The robot should provide a meaningful educational function that would be difficult or less effective to achieve through another method.

Third, how will learning be assessed? Assessment should focus on what students learned rather than on whether they successfully operated the robot.

Project-based learning, inquiry-based learning, constructionism, collaborative learning, and experiential learning are particularly compatible with educational robotics because students can actively design, manipulate, test, and revise solutions.

9. Implications for K–12 Education

Schools seeking to introduce robotics should consider a gradual and evidence-informed implementation strategy.

1. **Curriculum Alignment:** Robotics activities should be directly connected to curriculum objectives in science, mathematics, technology, computing, languages, or other subjects.
2. **Teacher Professional Development:** Teachers should receive continuing professional development that combines technical and pedagogical competencies.
3. **Infrastructure Planning:** Schools should assess electricity, connectivity, computer availability, classroom space, maintenance requirements, and technical support before implementation.
4. **Equity and Accessibility:** Robotics programs should be accessible to learners regardless of socioeconomic status, gender, disability, or prior technological experience.
5. **Ethical Governance:** Schools should establish policies covering privacy, data protection, safety, algorithmic bias, transparency, and appropriate use of AI-enabled robots.
6. **Evaluation:** Schools should evaluate robotics programs using meaningful educational outcomes, including academic achievement, problem-solving, computational thinking, motivation, collaboration, and teacher workload.

10. Future Research Directions

Although the evidence base for educational robotics is growing, several research gaps remain.

First, more long-term studies are needed. Much robotics research has involved short interventions, making it difficult to determine whether initial enthusiasm and learning benefits are sustained.

Second, more research is required in authentic classroom environments. Woo et al. (2021) found that relatively few studies involved long-term, autonomous deployment of social robots in real classrooms.

Third, research should examine the interaction between teachers and robots rather than focusing exclusively on student–robot interaction.

Fourth, researchers should investigate the cost-effectiveness of robotics programs, especially in low- and middle-income educational contexts.

Fifth, future studies should examine how AI-enabled robots affect children's privacy, autonomy, social development, and understanding of technology.

Finally, more comparative research is needed to determine when robotics offers educational advantages over conventional teaching and other forms of educational technology.

11. CONCLUSION

Educational robotics represents an important emerging technology for K–12 education. Its applications extend from early childhood coding and storytelling to advanced STEM, programming, engineering,

language learning, and personalized educational activities. Research reviews and meta-analyses provide evidence that robotics can produce positive learning outcomes under appropriate conditions (Benitti, 2012; Wang et al., 2023; Ouyang & Xu, 2024; Lu & Geng, 2026). However, the evidence does not support the simplistic idea that robots can replace human teachers. Social-robot research conducted in authentic classroom settings has identified substantial challenges involving autonomy, personalization, technical reliability, ethics, and long-term deployment (Woo et al., 2021).

The most appropriate interpretation of robotics in K–12 education is therefore one of augmentation rather than replacement. Robots can provide opportunities for physical interaction, experimentation, immediate feedback, repetitive practice, programming, and personalized activities, while human teachers provide relationships, judgment, creativity, mentorship, emotional support, and pedagogical leadership.

The future of robotics in education is consequently likely to depend not on developing machines that simply imitate teachers, but on designing effective human–robot learning environments. When robotics is aligned with curriculum objectives, supported by competent teachers, implemented ethically, and evaluated through meaningful learning outcomes, it can become a valuable component of K–12 education.

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