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A Systematic Review of Studies on Educational Robotics

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A Systematic Review of Studies on Educational Robotics

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Abstract

There has been a steady increase in the number of studies investigating educational robotics and its impact on academic and social skills of young learners. Educational robots are used both in and out of school environments to enhance K–12 students' interest, engagement, and academic achievement in various fields of STEM education. Some prior studies show evidence for the general benefits of educational robotics as being effective in providing impactful learning experiences. However, there appears to be a need to determine the specific benefits which have been achieved through robotics implementation in K–12 formal and informal learning settings. In this study, we present a systematic review of the literature on K–12 educational robotics. Based on our review process with specific inclusion and exclusion criteria, and a repeatable method of systematic review, we found 147 studies published from the years 2000 to 2018. We classified these studies under five themes: (1) general effectiveness of educational robotics; (2) students' learning and transfer skills; (3) creativity and motivation; (4) diversity and broadening participation; and (5) teachers' professional development. The study outlines the research questions, presents the synthesis of literature, and discusses findings across themes. It also provides guidelines for educators, practitioners, and researchers in areas of educational robotics and STEM education, and presents dimensions of future research.

Keywords: educational robotics, educational robots, systematic review, K–12 education, STEM education

Introduction

Robots inspire us to wonder about the world we may experience in the future. For example, many people marvel at the sight of a tiny drone aircraft hovering above us, wish for a Rosie (or Roomba) to do daily chores, or long for a companion like R2-D2 of Star Wars. This initial attraction can lead to a deeper connection with many technical aspects of robotics, including robotics use in education. Broadly, integrating robotics in an educational setting can lead to an interest in STEM (Science, Technology, Engineering, and Mathematics) topics and allow deeper engagement of students on complex concepts (Melchior, Cohen, Cutter, & Leavitt, 2005). Educational robots have been used for various reasons such as instructional materials (Lau, Tan, Erwin, & Petrovic, 1999; Wang, 2004), learning companions (Kory & Breazeal, 2014; Kory, Jeong, & Breazeal, 2013), and teaching assistants (Han & Kim, 2009; You, Shen, Chang, Liu, & Chen, 2006). K–12 educational robots and robotics competitions have emerged as highly popular educational activities that actively engage children in critical thinking and problem solving in team settings (Menekse, Higashi, Schunn, & Baehr, 2017). Accordingly, there has been a steady increase in the number of research studies investigating educational robotics and their impact on academic and social skills of young learners (e.g., Alimisis, 2013). However, systematic reviews are needed for full integration of the current knowledge base on the effectiveness of educational robotics in both formal and informal settings.

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While some studies demonstrate the role of educational robotics to enhance student interest and engagement (Rubenstein, Cimino, Nagpal, & Werfel, 2015), little evidence is available across studies to reach a conclusion regarding the relative effectiveness of educational robots on students' learning outcomes and professional skills (e.g., communication, collaboration). Also, most studies lack details about the implementation of educational robotics within and outside school environments. Although growing bodies of literature regarding robotics use in K–12 education exist (e.g., Alimisis, 2013; Barker & Ansorge, 2007; Eguchi, 2014; Hendricks, Alemdar, & Ogletree, 2012; Menekse, Higashi, Schunn, & Baehr, 2017), there is a need to connect the theoretical basis of robotics usage with its implementation. The research goals that guide this systematic review study are to explore the main purposes of educational robotics usage in K–12 formal and informal learning settings and the benefits achieved with its implementation, as well as to synthesize the main findings across studies. To address these research goals and identify the common themes in literature, we systematically reviewed the literature about educational robotics within K–12 STEM education.

Our review regarding educational robots in both formal and informal learning environments covered studies published from the years 2000 to 2018. We used a systematic review approach and classified a total of 147 studies. Each study was reviewed based on its theoretical framework and results. Further, we synthesized studies to identify common themes encountered throughout the research discussing the effectiveness of robotics in existing literature. This study analyzed the literature with three goals: (1) to determine recurring themes in studies investigating K–12 robotics implementation; (2) to present empirical evidence about the benefits of using educational robots; and (3) to define research perspectives in educational robotics to aid in developing and improving STEM pedagogies.

The paper is structured into eight sections. Section two presents a brief review of the literature on educational robots indicating the unique role of robotics in education. Section three outlines the purpose of this study. Section four addresses the research methods of this study, describing the systematic evaluation, selection, coding, and synthesis methodologies. Section five outlines the findings, including identified themes presented alongside exemplary studies. Section six summarizes the findings, section seven provides limitations, and the last section provides a conclusion with future directions.

Educational Robotics

Ever since LOGO programming language was first developed in 1967, educational robotics has become an important pedagogical tool for K–12 STEM education. The frequency of robotics usage has exploded in the past two decades, especially after the collaboration between LEGO Group and the Massachusetts Institute of Technology (MIT) Media Lab to develop educational robotics for mass markets called MINDSTORMS. According to LEGO Education North America sales figures, over 60,000 formal and informal education providers in the United States have purchased MINDSTORMS robots, and their use has greatly expanded as evidenced by growth curves in LEGO-based competitions. Today, with a flock of interest in the maker movement, the number of tinkerers, novices, designers, and engineers who combine easily accessible information with personalized technologies and become active makers, instead of passive users of products and tools, is steadily increasing across age groups. Robotics competitions and maker fairs are stimulating intrinsic motivations for innovation and creativity. These informal settings have the potential to provide an ideal venue that could tacitly nourish children's life-long learning skills through curiosity, observation, and interactive activities.

Theoretical Context of Education Robots

Historically, the fundamental theory that accounts for the role of educational robots is constructivism (Bruner, 1997; Ginsburg, 1988; Piaget, 1970). The premises of constructivism consider knowledge as an experience that is actively constructed through interaction with the environment (Piaget, 1970). Based on constructivism, learners typically work on authentic problems in small groups or student teams. Learners' prior experiences and prior knowledge are the basis for constructing further knowledge. Furthermore, the process of knowledge construction and formative assessments are as important as the final product and summative assessment. This mechanism of working on authentic problems encourages generating solutions by employing technological framework meant to engage and motivate students (Papert, 1993).

The second theory, which is in line with the primary purpose of using robotics to enhance student learning, is constructionism (Papert, 1980; 1993). This theory shares ideas with constructivism, but expands it by providing real-world context to guide the generation of new knowledge (Papert, 1980). In this way, constructionism as a theory supports student-centered learning and also places emphasis on discovery learning with tangible objects and making connection between prior knowledge and new information in the real world (Alimisis & Kynigos, 2009). The main difference between constructivism and constructionism is that while constructivism primarily refers to the mental processes of learners, constructionism mainly indicates physical processes (e.g., constructing a physical model, generating a mathematical equation, etc.) (Ackermann, 2001). Thus, constructionism considers both construction and deconstruction, and makes the process of thinking and learning visible by engaging students in a process-oriented task.

Early Eduational Robots

Seymourt Papert's pioneering work during the 1980s showed that young children could learn the LOGO programming language and code the "turtle" robots to solve problems. The idea was based on the unique features of educational robotics. The educational robots provide opportunities for students to engage in both coding (i.e., programming) and non-coding (i.e., creativity, abstraction) aspects of computer science starting at an early age. In light of this feature and in order to engage young students, MIT Media Lab, in collaboration with Seymour Papert, developed the LEGO MINDSTORM line of robotics hardware and software used in many K–12 robotics competitions. The system draws its name—MINDSTORMS—from Papert's 1980 book *Mindstorms: Children, Computers, and Powerful Ideas*. Papert was also one of the developers of the LOGO programming language, which later provided the basis of constructionism (Papert, 1986; Papert & Harel, 1991). The LOGO language was designed to help children build computer programming skills and knowledge. The constructionist curriculum focused on problem-based learning scenarios in which students could have the ability and need to build skills as part of the process of solving a larger problem. Thus, skills are acquired while constructing a solution to a problem. A good problem will require, suggest, and support the development of the appropriate skills. A robotics competition, then, might be the best opportunity to provide a problem and the environment in which to construct a solution. The quality of such a program would be measured through its ability to assess the right kinds of learning, as much as what kinds of learning it produces.

Use of Robots in Education

Beginning with Papert's work (1980) there have been several studies on utilizing educational robots to teach various STEM concepts (e.g., Klahr & Carver, 1988; Mason & Cooper, 2013; Touretzky, 2013). Early studies on educational robotics primarily focused on teaching computer programming, as Papert was one of the developers of the LOGO programming language. More recent studies are primarily focusing on a broader set of computer science concepts and skills called "computational thinking" (e.g., Bers, Flannery, Kazakoff, & Sullivan, 2014; Wing, 2006; 2008).

In addition to computer-science-specific studies, there are a significant number of studies on educational robotics with a focus on multiple STEM-related concepts and skills. Some studies have shown that educational robotics have a positive effect on students' critical thinking and problem-solving skills (e.g., Okita, 2014). A few of these studies have illustrated that educational robotics can increase students' interest and engagement in STEM (e.g., Kim, Kim, Yuan, Hill, Doshi, & Thai, 2015; Mohr-Schroeder et al., 2014), proportional reasoning skills (Alfieri, Higashi, Shoop, & Schunn, 2015), and learning of mathematics (Martinez Ortiz, 2011), physics (Williams, Ma, Prejean, Ford, & Lai, 2007), and science literacy (Sullivan, 2008). On the other hand, some studies reported no significant gains in student learning (Barker & Ansorge, 2007; Hussain, Lindh, & Shukur, 2006), or significant effects for some sub-groups of students (Lindh & Holgersson, 2007).

Robotics also has a multidisciplinary nature that integrates STEM disciplines (Grubbs, 2013; Johnson, 2003; Khanlari & Kiaie, 2015). Khanlari and Kiaie (2015) explored teachers' perceptions of the use of robotics in STEM fields. In addition, the authors found that robotics could promote students' thinking in STEM courses (Khanlari & Kiaie, 2015). Merdan, Lepuschitz, Koppensteiner, & Balogh (2017) suggested that the use of robotics brings innovative engagement in STEM classrooms and fosters problem-solving and teamwork skills. Similar results are reported in an empirical research study conducted by Kim and colleagues (2015), where the findings suggest that the use of robotics can increase STEM engagement and improve student attitudes toward STEM education. Furthermore, some studies argued that educational robots can foster students' skills in writing, reading, collaboration, and communication (Alimisis & Kynigos, 2009; Atmatzidou, Markelis, & Demetriadis, 2008; Carbonaro, Rex, & Chambers, 2004)

Overall, there has been a steady increase in the number of educational research studies that have investigated educational robotics and its impact on the skills and social and academic knowledge of young learners (e.g., Alimisis, 2013; Barker & Ansorge, 2007; Eguchi, 2014; Hendricks, Alemdar, & Ogletree, 2012; Witherspoon, Schunn, Higashi, & Baehr, 2016).

Robots and Educational Setting

Prior literature gives evidence of a range of settings in which educational robotics programs have been employed. For instance, many research studies explored the effectiveness of educational robots in school settings (Bers & Urrea, 2000; Dias, Mills-Tettey, & Nanayakkara, 2005; Resnick, 1993), in technical and vocational schools (Alimisis, Karatrantou, & Tachos, 2005), after-school programs (Barker & Ansorge, 2007; Rusk, Resnick, Berg, & Pezalla-Granlund, 2008), summer camps (Balaguer Alvarez, 2017; Barger, Gilbert, & Boyette, 2011; Doerschuk, Liu, & Mann, 2007; Ericson & Mcklin, 2012; van Delden & Yang, 2014), project-based learning environments (Carbonaro et al., 2004), and various STEM fields (Hussain et al., 2006; Williams et al., 2007; Nugent et al., 2010). Prior studies argued that educational robotics and participation on a robotics team have the potential to significantly influence a child's academic and social skills by allowing them to actively engage in critical thinking and problem solving through designing, assembling, coding, operating, and modifying robots for specific goals (Menekse, Higashi, Schunn, & Baehr, 2017). For that reason, most school programs and after-school programs, weekend clubs, summer camps, makerspaces, and education programs within museums have integrated educational robots into their programs to empower children with critical thinking, problem solving, and professional skills. For example, Ericson and Mclin (2012) used summer camps to socially engage students in creative computing tasks using PicoCrickets, LEGO NXT kits, and LEGO WeDO kits to design a musical pickle, spin art, and plane, respectively. The investigators conducted the study with goals of increasing diversity and enhancing students' learning by engaging them in creative student-led projects. They used paired pre- and post-surveys to evaluate the camps and reported positive attitude changes in students. They also found that students' learning of concepts was increased as a result of engaging activities in summer camps.

Since there has been a significant interest in educational robots, it is important to explore these efforts to understand how robotics has been used as an innovative tool, and to conduct comparative studies which investigate the relative effectiveness of educational robots in comparison to other approaches.

Purpose of This Study

Although educational robotics is considered an innovative instructional tool in and out of classroom environments, the effectiveness of the use of educational robotics is often presupposed. The literature has evidence of few existing review studies on robotics in K–12 spaces (i.e., Benitti, 2012; Karim, Lemaignan, & Mondada, 2015; Toh et al., 2016; Xia & Zhong, 2018). These studies differ from the current study for two primary reasons: (1) the research questions; and (2) the number of studies included in the review—all prior reviews had a smaller number of studies included. Furthermore, the limited inclusion of studies provided a limited conception (Bascou & Menekse, 2016). Table 1 shows a brief overview of prior review studies.

Benitti's (2012) study considered the benefits of introducing robotics tools and platforms to teach various topics. Benitti's review explored the effectiveness of educational robotics, focusing on studies of robotics in school classrooms but not including those in informal settings. Benitti's review provided a sound base for the current analysis; however, it had several limitations such as a limited number of studies, use of only quantitative evaluation of the learning, and not accounting for the underlying theoretical foundations that made specific forms of robot-based pedagogies more efficient. Also, since teaching and learning practices in formal and informal environments differ, to fully understand how educational robotics affects children's academic, motivational, and social skills, the integration of the current knowledge base on the effectiveness of educational robotics in informal learning environments is also needed through a systematic review using a rigorous design.

Karim and colleagues (2015) also reviewed literature on educational robots such as LEGO Mindstorms ("LEGO Group. LEGO Mindstorms ev3."), VEX IQ Super Kit ("Vex Robotics. Vex iq super kit."), and Hemission ("K-Team Corporation. K-team robots."). They identified several shortcomings in robotics platforms and teaching environments and suggested having an educational framework that combines robots and augmented reality. The study emphasized the importance of having pedagogical modules. However, this study, in addition to the limited number of included studies, failed to indicate the effective robotic pedagogies and theoretical foundations that are required for educational modules in STEM education.

The study focus of Toh and colleagues (2016) was limited to the use of robotics in early childhood and lower level education. The authors examined the influence of robots on children's behavior and development, and their reaction to the robot's appearance and visual characteristics. Thus, both the focus and intent of the study is different from the current study.

The recent review study by Xia and Zhong (2018) used the "snowballing approach" to identify the papers.

Table 1
Primary research questions and the number of included studies in prior review studies.

Authors	Major Research Question(s)	Included Studies
Benitti, (2012)	What are the benefits of incorporating robotics as an educational tool in different areas of knowledge?	10
Karim et al., (2015)	Can robots in the classroom reshape education and foster learning?	18*
Toh et al., (2016)	What is the influence of robots on the behavior and development of early childhood and lower level education?	27
Xia & Zhong, (2018)	How have robotics been incorporated in K–12? What intervention approaches are effective in teaching and learning robotics content knowledge?	22

* Based on the study's (Karim et al., 2015) Table 1: Summary of the topics covered in educational robotics featuring mathematics and physics (p. 1).

They examined each paper for nine factors: sample groups, duration, robot types, content knowledge, study type, intervention mechanism, instruments, findings, and instructional suggestions. In light of their findings, the authors proposed having more intervention studies with focused research design in K–12 spaces. However, this study, while addressing important questions, was lacking on several grounds:

1) The authors used an artificial criteria of limiting studies to journal articles only. This artificial criterion is used to indicate the quality of papers in the fields of computer science, computer engineering, and electrical engineering. However, quality literature is also found in conference proceedings of ACM, IEEE, and ASEE conferences.
2) The authors used "snowballing approach" on the basis of three selected articles. The snowballing approach is not a repeatable process, which questions the basic credibility of the systematic literature review.

Acknowledging the limitations of these existing reviews, we believe it is essential to provide a more holistic portrayal of the research on educational robots. We reviewed the literature in a manner that not only captures how and in what subjects teachers and researchers have attempted to use educational robotics, but more importantly, highlights the complex psychological, organizational, and cultural mechanisms that influence the capacity for robotics to enhance students' motivation and learning outcomes. However, like the above studies, our goals demanded that we develop a systematic manner to organize the studies.

Research Methods

In this study, we used the systematic literature review methodology to search, review, and analyze the existing literature. To conduct the systematic literature review, we used Borrego, Foster, and Froyd's (2015) four complementary methods: search, selection, coding, and synthesis.

Search Method

To begin our examination of the relevant literature, we first searched the following research databases: ACM, IEEE Xplore, ERIC, and ASEE Annual Exposition and Conference Proceedings. The search was performed twice in the last few years: (1) June 2014 and (2) September 2018 using the search protocol depicted in Table 2.

Selection Strategy

The 635 studies were analyzed based on our inclusion and exclusion criteria (Table 3). We excluded 488 articles based on five exclusion principles and full-text review. These principles are non-compliant sample properties (139), secondary or tertiary source articles (59), irrelevant nature of articles (120), non-relevance to current study (58), and incomplete or duplicates (34). Further, full-text reviews excluded 78 other studies for nonrelevance to current study on robotics. Two of the authors of this study collaboratively worked on deciding to include or exclude a study by using the exlusion principles provided in Table 3. Figure 1 describes the flow of information through the stages of identification, screening, eligibility, and inclusion.

Table 2
The search protocol for the review.

Database	Search Protocol
ACM Digital Library	Search String: (Education OR educational) AND (STEM) AND (Learning) AND (elementary OR middle OR High OR K–12) AND (Robotics OR Robots) Used advanced search to create the same query by using fields Searched in: ACM Full-Text Collection
IEEE Xplore	Search String: (Education OR educational) AND (STEM) AND (Learning) AND (elementary OR middle OR High OR K–12) AND (Robotics OR Robots) Used advanced search to create the same query by using fields Searched in: Full Text & Metadata
ERIC	Search String: (Education OR educational) AND (STEM) AND (Learning) AND (elementary OR middle OR High OR K–12) AND (Robotics OR Robots) Searched in: Peer-reviewed only
ASEE Annual Conference and Exposition	Search String: Education Educational + STEM + learning + elementary middle high K–12 + robotics robots Searched in: each annual conference individually
Other Source	Used studies included in Xia & Zhong (2018) as another source to ensure all these studies are also part of our review (if not already included)

The four databases yielded 232, 39, 48, and 294 studies, respectively. Additionally, we found 22 studies from Xia and Zhong's (2018) review. Overall, we found a total of 635 studies.

Table 3
Criteria for the exclusion of studies.

Exclusion Principle	Description
Sample Properties	Articles in this category did not contain the desired age group (i.e., undergraduates, professionals, or any other cohort not at the K–12 level), have a very small sample size (i.e., $N < 10$), or failed to disclose essential information regarding the participants.
Secondary or Tertiary Source	Articles in this category did not present a primary study. Most were syntheses that compared and contrasted work of various researchers or attempted to extrapolate findings from other studies.
Nature of Article	Articles in this category did not exhibit the desired format of the article. Most of them were expert interviews, editor's notes, or summaries of a person's work or theory.
Relevance	Articles in this category showed no direct connection. They often involved innovations in computing or robotics but failed to address education.
Publication Date/ Abstract only/ Repetition	Articles in this category were published before 2000, only made available the abstract in the database, or were repetitions of other articles seen previously.

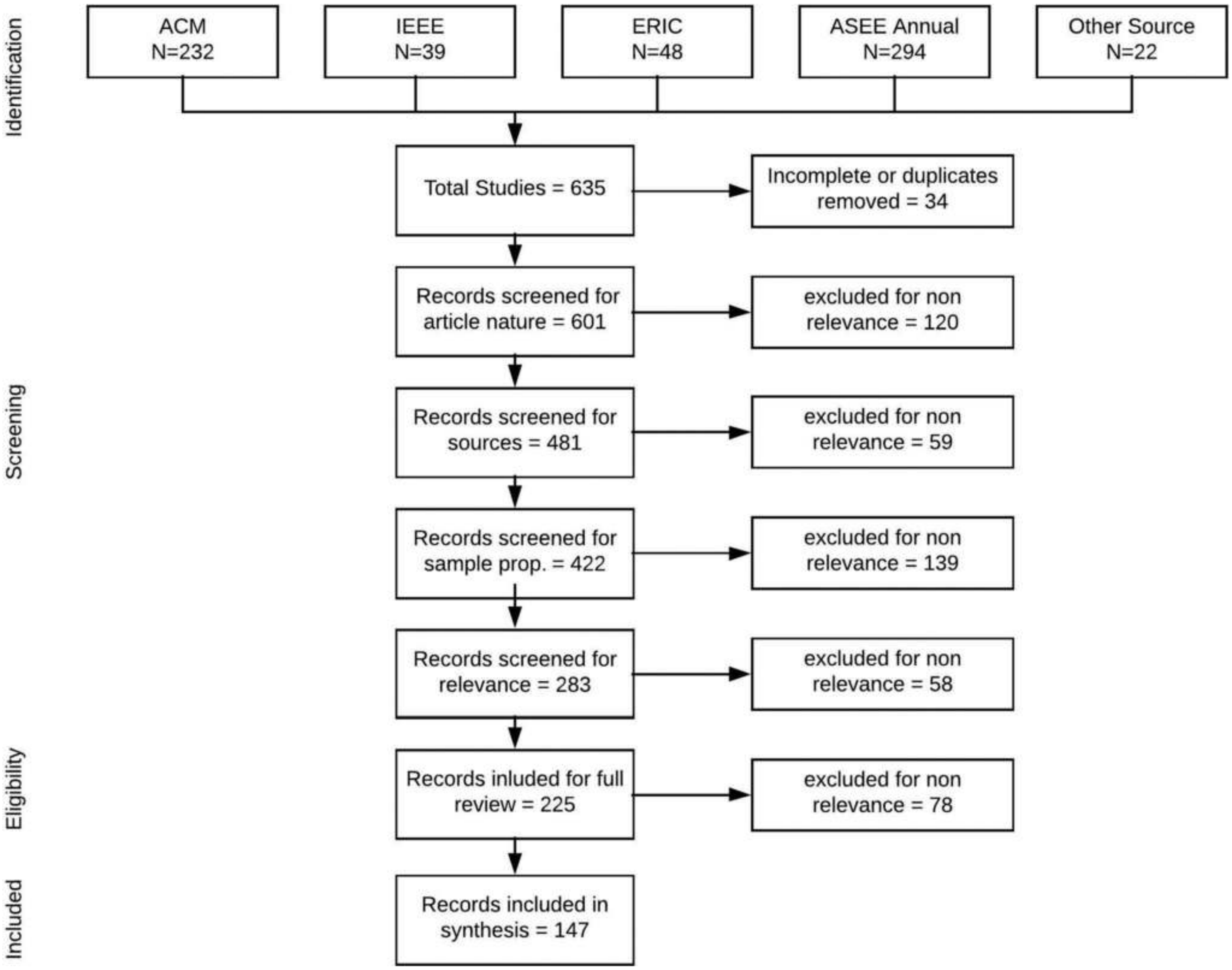

Figure 1. Study inclusion and exclusion flowchart based on the PRISMA–Flow of information through stages (Moher, Liberati, Tetzlaff, & Altman, 2009).

Based on the exclusions principles, 147 studies were included in this literature review. Please see Appendix A and B for the complete list of reviewed studies.

Figure 1 shows the study inclusion and exclusion flowchart based on the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) checklist for our research purposes (Moher, Liberati, Tetzlaff, Altman, & Prisma Group, 2009). The PRISMA checklist is an extensively used protocol for systematic reviews and meta-analysis across disciplines to ensure high-quality reviews (e.g., Nordheim et al., 2016; Polanin, Maynard, & Dell, 2017).

Coding and Synthesis

We initially documented and classified all studies on the basis of seven features: (1) experimental vs. non-experimental research design; (2) formal vs. informal learning environments; (3) whether the investigation included student-learning data; (4) types of robotics platforms; (5) sample properties; (6) primary goal(s) of the study; and (7) primary results and findings. We also explored commonalities in research methodologies, results, and subsequent findings of these 147 studies. We classified articles based on prevalent themes. The five identified themes are: (1) general effectiveness of robotics in education; (2) students' learning and transfer skills; (3) creativity and motivation; (4) diversity and broadening participation; and (5) teachers' professional development.

We observed that although most articles followed one category or theme only, there are 27 articles that could be classified under more than one theme. After assigning each article to a theme, we summarized and discussed the representative studies.

To develop a systematic model in which to organize the studies, we began by classifying the studies based on their commonalities. Once all the databases were exhausted of relevant primary studies, we ascribed each cluster with a brief description. This description was used to depict typical trends found in the studies of the cluster. Furthermore, to refine the rationale behind the groupings, we studied the secondary and tertiary sources of these studies. These sources provided insight into the distinctions and individual elements of the studies and helped to identify their unique aspects. Also, these sources provided information on how each study differs from the others based on their goals, theoretical frameworks, and findings. We used this information to devise our coding scheme for all the articles, and we merged the codes into categories and themes. We combined the redundant themes as well.

Findings

These 147 articles were reviewed to identify their primary classification and qualitative thematic analysis (please see Appendix A and B for all 147 studies). For basic classification, all articles were categorized based on information about their research settings, research designs, and publication types. We observed that the majority of studies lacked an experimental or quasi-experimental design. Also, we found that more studies were conducted in informal learning settings such as summer camps rather than formal learning settings such as classrooms. Also, in these selected articles, there were more conference papers than journal articles. Moreover, a majority of the studies (i.e., 67%) reported use of a version of LEGO Mindstorms. Table 4 indicates the primary differentiation of these articles.

Table 4
Primary differentiation of articles based on setting, design, and publication type.

Differentiation Type	**Classification**	
Setting	Formal	Informal
	69	78
Design	Experimental	Non-Experimental
	42	105
Publication Type	Journal	Conference
	61	86

Table 5
Distribution of 147 articles based on the thematic classification.

Themes	**Number of Articles***
General benefits of educational robotics	45
Learning and transfer skills	32
Creativity and motivation	53
Diversity and broadening participation	16
Teachers' professional development	28

* A total of 27 articles were classified for two themes.

For the qualitative thematic analysis of these 147 articles, we conducted an investigation based on commonalities found in the research methodologies, results, and subsequent findings. We further considered demographic features, tools used for student motivation, and pedagogical approaches. Considering the obtained results of the analysis, we classified these articles into five themes. There were 27 studies which were multi-themed and classified accordingly. Table 5 shows the number of studies categorized under each of the categories and themes.

Theme 1: General Benefits of Educational Robots

The first theme addresses the general benefits of educational robots. We found a total of 45 studies that addressed the general benefits of robotics usage in K–12 education without focusing on more specific aspects. These studies focused on the idea that there is a broad benefit to using educational robotics with K–12 students, but they typically do not highlight a particular focus. These studies unanimously suggested that robotics promotes active-learning pedagogy and helps to improve the learning experience. The studies in this theme have used educational robotics to integrate engineering design in curriculum courses or after-school programs (Mosley, Ardito, & Scollins, 2016; Sahin, Ayar, & Adiguzel, 2014; Silk, Higashi, & Schunn, 2011; Taban, Acar, Fidan, & Zora, 2005), critical thinking and inquiry (Ganesh et al., 2010;

Sahin et al., 2014; D. C. Williams, Ma, Prejean, Ford, & Lai, 2007), and other developmental competencies (e.g., confidence, etc.) (Barger et al., 2011; Mac Iver & Mac Iver, 2014).

As an exemplary study of this theme, Sahin and colleagues (2014) described the effectiveness of six STEM-related after-school activities. The authors used qualitative case study design to understand and analyze students' views about activities and reported that such robotics activities with high use of design processes helped students to work in collaborative environments and partnerships, and to demonstrate uses of various 21st century skills such as commitment, problem solving, and ownership of work.

In another study, Williams and colleagues (2007) found evidence validating the effectiveness of educational robotics for students. The authors evaluated the impact of a robotics summer camp on students' physics content knowledge and scientific inquiry skills by using pre-and post-analysis. The analysis indicated a significant difference of physics content knowledge measured by pre-tests and post-tests ($M_{\text{pre}} = 8.40$; $M_{\text{post}} = 9.75$; $p = 0.004$). For inquiry skills, researchers reported that students showed less interest in traditional lessons and were more inclined to participate in robotics building and programming tasks. However, no statistically significant differences were found when comparing pre-test and post-test scores for the scientific inquiry measure.

Overall, these 45 studies under the first theme had a broader focus and indicated that incorporating educational robots in formal and informal learning settings is valuable for students to enhance their academic success and/or professional skills.

Besides addressing general benefits, some studies focused on the use of robotics for more specific purposes. We classified these studies into four other themes: enhancing students' learning and transfer skills, increasing creativity and motivation, enhancing diversity and broadening participation, and improving teacher professional development.

Theme 2: Learning and Transfer Skills

The theme of learning and transfer skills category includes studies that used robotics to enhance students' construction of new knowledge. The category emphasized that with the use of robotics, students can be engaged in an active-learning process, where they will construct new knowledge based on a hands-on experience and by engaging with certain tasks. In the process of using robotics, students learn and construct new knowledge through inquiry, exploration, and making the cognitive association with prior experience. We observed that 32 studies showed relevance to this theme. These studies explicitly examined either: (a) how hands-on learning experience with robots allows students to understand abstract concepts better (e.g., Krishnamoorthy & Kapila, 2016; McGrath et al., 2008; Shankar, Ploger, Nemeth, & Hecht, 2013; K. Williams, Kapila, & Iskander, 2011); or (b) promotes students' ability to transfer knowledge learned through experiences to a novel setting or problem (e.g., Ganesh & Thieken, 2010; McKay, Lowes, Tirhali, & Camins, 2015; Sánchez-Ruíz & Jamba, 2008).

As an exemplary study for this category, Williams and colleagues (2012) assessed the effectiveness of an after-school program in implementing hands-on robotics activities. They considered robotics as a tool for facilitating elementary school children's understanding of mathematical concepts outside of a traditional classroom setting. The researchers designed three interactive, team-based LEGO activities. Based on data collected in pre- and post-evaluation surveys, all three lessons demonstrated that students improved their conceptual understanding of the content after participating in the activity. Additionally, students showed increased interest in and motivation to learn math through team activities. Moreover, these activities exposed students to real-world applications of mathematics outside the classroom.

In terms of transferring knowledge to a new context, Sanchez-Ruiz and Jamba (2008) evaluated the success of an extracurricular educational robotics program qualitatively. The program aimed to help students in grades 4–5 establish connections between acquired mathematical skills and computer programming. Further, the program was designed to help students understand how computers work and to help them build software using Squeak over a two-week period. Based on surveys and student feedback, the authors demonstrated the benefits of using educational robots to facilitate students' ability to apply and transfer mathematical skills in programming.

Overall, studies for this theme supported the notion that when students can observe a program realized in robotics behavior, they are provided with the opportunity for a fascinating experiment in which ideas, scientific theories, and computer coding merge with the real world. In this way, educational robots may help students gain experiences that will facilitate a deep and abstract understanding required for constructing knowledge and enhancing critical thinking (Nugent et al., 2010). In this context, "deep" implies the ability to recognize key concepts applied in the appropriate programming context, while "abstract" means the capacity to separate the essence of a mechanism from the syntactical details (Touretsky, 2013).

Theme 3: Creativity and Motivation

We found 53 educational robotics studies that addressed creativity and student motivation. These studies considered motivational aspects of a social or cultural trend, or creativity in pedagogy to improve students' motivation and interest in the subject (e.g., STEM courses, especially programming). These studies are driven by the idea that robotics can be a tool to encourage and enhance students' interest in learning STEM concepts (Cuellar et al., 2014; Eguchi & Uribe, 2012). Further, by using the design of everyday experiences across settings and social groups, these studies showed that engaging with educational robots has the potential to promote students' creativity (e.g., Giannakos, Jaccheri, & Proto, 2013; Hamner & Cross, 2013; Nemiro, Larriva, & Jawaharlal, 2017).

Some studies found significant effects regarding the increase in student interest and motivation to study STEM with new trends and technologies. For example, Master, Cheryan, Moscatelli, and Meltzoff (2017) conducted a study with 96 six-year-old children and addressed the stereotype of boys being better than girls in STEM fields. They used randomly assigned control and treatment groups, where the treatment group was given programming experiences by using educational robotics, and the control group was not given any educational robotics experience. The study reported higher technology interest and higher self-efficacy in students who were in the treatment group compared to students in the control group. Furthermore, the study found no gender gap between boys and girls in this regard.

To explore the role of educational robotics on students' interest and motivation, Cuellar and colleagues (2014) used both quantitative and qualitative analysis approaches at a robotics education workshop. There were 12 participants in the workshop and researchers collected multimodal data, such as video-recordings of activities, participants' behavioral observations, and an evaluation rubric, to assess the performance of the participants. The study reported that design and implementation of unique and innovative educational robotics enhances student engagement in these activities, as well as their interest in science and technology.

In these studies, we observed that one of the factors that helped to increase student motivation and interest was using creative outlets. Shanahan and Marghitu (2013) argued for the potential benefits of using activities to promote creativity of middle school students in a program called Project Expression. The program focused on a film project, where participants were tasked with creating a movie that expressed an idea or belief about society using robotics platforms such as LEGO robotic platforms and virtual Alice platforms. During the program, participants were trained in java programming and the art of multimedia production. Based on 71 student surveys, the results showed that Project Expression represents a valuable example of a multimedia-based learning experience that draws students into the field of computer science and software engineering.

In general, the studies indicated that incorporation of creativity into the early stages of computing and STEM education functioned as a catalyst. This catalyst moved in two directions simultaneously, as it diminished the learning curve and increased interest among novices. However, despite the benefits of incorporating creativity in early STEM education, the same positive results have not been obtained at more advanced levels, lending way to the argument that, while useful for beginners, the benefits of creativity decrease as students progress down the STEM pipeline.

In sum, studies in this theme often focused on robotics learning activities that appear closer to everyday life aspects, and explored the role of educational robotics on motivational and creativity-related constructs. Furthermore, some studies in this theme argued that robotics helps educators to design socially and culturally relevant learning activities and units, which can enhance students' creativity and motivation.

Theme 4: Diversity and Broadening Participation

We found 16 studies that explored the effect of educational robotics as an effective tool to broaden the participation of underrepresented groups. These studies focused on increased participation or retention of females (Mason, Cooper, & Comber, 2011; Master et al., 2017; Terry, Briggs, & Rivale, 2011), minorities (Kafai, Searle, Martinez, & Brayboy, 2014; Searle, Fields, Lui, & Kafai, 2014; Shatz, Pieloch, & Shamieh, 2016; Zimmerman, Johnson, Wambsgans, & Fuentes, 2011) or other underrepresented populations in STEM fields (Dorsey & Howard, 2011; Rosen & Newsome, 2011; Siraj, Kosa, & Olmstead, 2012). Mason and colleagues (2011) described the success story of two workshops, developed and designed to encourage female high school students for careers in Information Technology. They used 3D programming activities designed using Alice environment and Mindstorms robots. They evaluated the success of these workshops by using pre- and post-questionnaires. They specifically addressed the research question of how students' programming skills changed as a result of these workshops, and primarily addressed this question by collecting data on students' confidence in solving problems by using programming. The results indicated that students perceived an increase in their programming skills as a result of the workshops. Further, the attitudes of both groups toward programming improved, and students reported higher confidence in their programming abilities. The authors also discussed the success of robotics intervention for changing students' perceptions regarding programming.

Searle and colleagues (2014) and Kafai and colleagues (2014) took a more holistic approach in their efforts to stimulate interest in African American, Latino, and Pacific Islander students. Searle and colleagues' (2014) program was designed for an individual's views and attitudes about the discipline. The researchers explored how students' attitudes and perspectives toward computing are shaped by engagement with robotic materials and how these relate (or fail to relate) to computational thinking. Ultimately, comparative analysis of pre- and post-surveys and interviews indicated that, upon completion of the program, students were better able to articulate a range of perspectives on computing, which could be linked to professional practice.

Summing up the 16 articles representing use of educational robotics with the goal of increasing diversity in STEM, numerous robotics summer camps and after-school programs have been designed to spark interest in underrepresented groups. In general, there were two study types: (1) studies considering exposure to STEM via robotics and have shown robotically based curriculum to be successful in improving students' interest (e.g., Mason et al., 2011); and (2) studies demonstrating the relatively greater success achieved by programs that integrate robotics with other forms of social, cultural, and creativity-based motivation, such as Searle and colleagues (2014), Terry and colleagues (2011), and Doerschuk and colleagues (2011). Overall, these studies focused on promoting diversity and retention in STEM fields by integrating educational robotics in school curricula or by using informal learning platforms to introduce educational robots as an intervention and means to encourage underrepresented students.

Theme 5: Teachers' Professional Development

We found 28 studies that utilized educational robotics to improve the professional development of teachers. To improve teacher efficacy, many school districts now offer Professional Development (PD) workshops with the goal of instructing teachers on how to effectively integrate robotics into their teaching. Goode and Margolis (2011) discussed that teachers exhibit knowledge, skill, and pedagogy gaps, which consequently inhibit efficient teaching. In order to reduce the gap of knowledge and improve their instructional strategies, K–12 educators are encouraged to attend PD workshops (Goode & Margolis, 2011; Harris & Hofer, 2011; Stubbs & Yanco, 2009). Alimisis (2012) highlighted the role of constructivist pedagogy and consequent educational methodologies, while training teachers to use robotics for instructional purposes. In this framework, constructivist methods for integrating robotics in physics and informatics education, as well as professional teacher training, were evaluated. The study addressed whether the workshop was effective in helping teachers to learn pedagogical techniques by assessing how their students performed in robotic design competitions following the workshop. Exemplary projects from each case were reported to illustrate the learning potential of the proposed educational methodologies, which involved the use of robotics to study kinematics and programming concepts in physics and informatics. In the two case studies (concerning the construction of a small automated vehicle), the respective teachers attended a workshop that instructed them to serve as experienced advisors to students, assisting them only when necessary. By doing so, researchers intended to maximize the educational benefits provided to children. To evaluate the effectiveness of the workshop, the teachers followed up the workshop by instructing students in a vehicular robotics competition. Alimisis (2012) argued that because groups were competing against one another, it provided incentive to optimize the vehicular designs. The teacher also played the role of experienced advisor and intervened infrequently. This allowed students to make most of the decisions themselves through trial and error. Alimisis (2012) compared the teaching methodologies employed by teachers before and after attending the workshop. He found that the new constructivist approach enhanced student knowledge and academic performance.

While face-to-face workshops are considered the most popular way to provide PD to teachers, the amount of time that workshops require may be inconvenient for teachers, thus discouraging them from attending. An alternative to face-to-face workshops comes in the form of online courses that operate with a similar goal of improving pedagogical approaches adapted for teachers. As of now, few school districts have used Massive Open Online Courses (MOOCs) to train their teachers in computer programming concepts. Spradling and colleagues (2015) briefly reviewed the history of MOOCs, reasons for offering MOOCs to K–12 teachers, and shared their experiences teaching three Google-funded MOOCs to K–12 teachers. The primary goal of the evaluated MOOC was to increase the effectiveness of teaching pedagogies that implement Scratch-based programmable robotics kits. In the surveys, researchers asked what type of MOOCs materials were the most beneficial. Of the responses, 23 stated that instructional projects containing directions in the use of Scratch robotics were most useful, with videos a close second (19). Nine reported that the virtual meetings were most helpful, and five believed that the online forum was most beneficial. Also, when asked how likely they would be to incorporate the course materials into their courses, 18 (72%) of the 25 respondents indicated they would probably include MOOC course materials. For various personal and professional reasons, when the survey respondents were asked to rate their current MOOC experience, the authors found that the largest portion (45.8%) thought the MOOC experience was better than a face-to-face workshop. Spradling and colleagues (2015) found preliminary evidence supporting the use of online courses as a means of enhancing the quality of teachers on a grand scale.

In summary, it is crucial to ensure that teachers are effective in conveying information and concepts to students in a relevant and comprehensible manner. To achieve large-scale success, we must find a way to train teachers in the most effective methodologies for fostering student learning via physical and virtual platforms, whether it be in the form of face-to-face workshops or online courses such as MOOCs. Overall, these studies indicated that educational robotics can be used in an effective way to train teachers using PD workshops for two specific reasons: (1) to introduce teachers to educational robots and enhance their knowledge and self-efficacy on robotics usage in their own classrooms; and (2) to engage teachers in robotics activities and curriculum design together, where teachers can provide immediate feedback on curriculum design and pedagogies, thus helping to improve and tailor the curriculum.

Limitations of the Study

Although we used a transparent mechanism of selection and inclusion, this study still has certain limitations. First, we included all studies that passed the inclusion criteria and relevance, and did not shortlist the studies based on their quality and reporting mechanism. This limitation is similar to what was noted by Slavin (1984) who highlighted the limitation of review studies and stated that they have less focus on the quality of the study itself. We overcame this bias by collecting data from authentic and reputed databases, which are known for including quality publications. Second, although we selected databases which included probable venues of publication of robotics papers, this selection was purely based on the authors' judgment. This criterion may introduce bias in the selection mechanism, and studies which are published at other venues may have not been part of this study. However, we tried to overcome this bias by doing a more inclusive search and including both conference and journal publications in our study. Third, like all systematic reviews, this study is limited by publication bias (Borrego, Foster, & Froyd, 2015). The publication bias is evident because of predominant favor in publication of positive results by both the authors and publication venues (Rothstein, Sutton, & Borenstein, 2006). We reduced this bias by including all studies that matched our criteria, which was not looking for positive results only. Also, as noted in the case of limitations of systematic reviews by Borrego, Foster, and Froyd, (2014), we selected a few studies for outcome reporting. The exemplary studies in our analysis were selected based on their relevance to the theme. To reduce this bias, we used peer selection mechanisms to select the exemplary studies. We reported the outcomes based on studies which were selected by two authors. Further, we included 147 studies (out of the 635) in our analysis, a large number of studies compared to most systematic reviews in educational sciences. The number could have been revised by adding more stringent criteria of inclusion at full-review stage other than mere relevance.

Discussion and Conclusion

Educational robots help students in a variety of ways, including the understanding of abstract concepts (Eguchi, 2014), providing them with a feedback-oriented learning environment (Bers, 2007), giving them a collaborative working environment (Eguchi & Uribe, 2012), and giving them opportunities to work and explore solutions to real-world problems (Miller, Nourbakhsh, & Siegwart, 2008). In general, with educational robots, students demonstrate improved knowledge (Nugent, Barker, Grandgenett, & Adamchuk, 2009), show positive attitudes toward science, engineering, and robotics (Miller et al., 2008), choose engineering as majors (Melchior, Cohen, Cutter, Leavitt, & Manchester, 2005; Scribner-MacLean et al., 2008), and engage in an iterative design process (Hamner, Lauwers, & Bernstein, 2010).

Based on our systematic review, we found a total of 147 studies published from the years 2000 to 2018. We classified these studies under five themes as: (1) general effectiveness of educational robotics; (2) learning and transfer skills; (3) creativity and motivation; (4) diversity and broadening participation; and (5) teachers' professional development. In this review, after evaluating each study and formulating detailed summaries, it was evident that research into educational robotics occurs at different levels and with various scopes. In the 32 studies that were classified in the theme of 'learning and transfer skills,' research questions were predominately formed to demonstrate the capacity of robotics to enhance students' abilities to actively construct and apply knowledge learned in one environment to a novel situation. For example, Touretsky (2013) suggested that robotics can support students in acquiring a deep and abstract conceptual understanding. These studies evaluated cognitive factors involved in teaching STEM education via robotic platforms by comparing control (non-robotic curriculum) and treatment (robotics-based curriculum) groups. Such comparative studies have been informative and have demonstrated the promising future of robotics in STEM education to increase students' ability to transfer knowledge. However, the short-term nature of many of these studies has limited the range of plausible conclusions that can be drawn. Thus, it is essential to have long-term follow-up studies.

A substantial portion of the 147 studies also took a step back, focusing less on the direct benefits of educational robots and instead concentrating on ways in which to motivate students via the integration of social, cultural, or aesthetic elements. Eguchi (2014) argued that educational robots typically motivate students and enhance their interest in STEM fields. The results, however, indicated that while a majority of these studies focused on promoting students' creativity and motivation via social, cultural, or creative avenues reported success, there were some studies that showed no effect (e.g., Delden & Yang, 2014; Wyffels et al., 2014). The success of such pedagogical approaches was often related to the background characteristics of the targeted student body, and students' prior knowledge about STEM-related concepts.

Acknowledging the lack of ethnic, socioeconomic, and gender diversity in STEM, 16 studies focused on increasing the proportion of women and minorities in STEM professions. Many underrepresented students are also disposed to having a strong aversion for STEM (due to misconceptions regarding the nature and relevance of the fields). So, researchers and educators are finding it beneficial to incorporate certain cultural, social, and aesthetic elements into their designed studies.

Bringing it all together, studies classified under 'teachers' professional development' took the broadest approach in their attempts to formulate the findings of micro-level research into fluid methodologies practical for teacher use. Studies of this theme typically evaluated teacher workshops that were designed to equip K–12 teachers with the skills and pedagogical approaches assumed to be most effective in maximizing student learning. Whereas face-to-face workshops have been investigated more thoroughly, the benefits of online courses are less explored, although open communication between those taking the course appears to be a requisite for success. In spite of the large number of studies dedicated to educating teachers about effective pedagogies, most abstained from using quantitatively rigorous methods of analysis, instead framing their results/findings based on anecdotal evidence from teacher feedback or surveys. Moreover, although many of the claims made regarding the improvement of teacher quality seem reasonable, some are invalid in a strictly statistical sense. To achieve substantiation, researchers will once again need to utilize more rigorous methods of analysis, similar to that seen in Alimisis (2012). Additionally, because teacher surveys from previous workshop assessments suggest that teachers continue to improve over an extended time frame, longitudinal studies tracking the participants throughout the years would be valuable in determining practices that make a workshop effective. Such research would be useful for developing professionals who are adequately prepared to integrate educational robotics to teach STEM concepts.

Overall, this systematic review has considered the use of educational robotics in both formal and informal learning environments. This study has shown that educational robotics has potential as a learning and teaching tool, including supporting the education of students who do not display immediate interest in academic disciplines related to science or technology. Our findings suggest educational robotics allows for an integrated, multi-disciplinary approach that incorporates technical and social topics. This approach encourages students to build mental connections and associations with the breadth of engineering, physics, and mechanistic concepts. To motivate students and optimize the learning process, it is imperative that researchers and K–12 teachers incorporate—in combination with robotic platforms—a wide range of cognitive and affective methodologies.

Future Directions

With this systematic literature review, we observed a few future directions in terms of both intervention design and research design. It is observed that future studies that utilize different assessment methods would be useful in substantiating the benefits of ethnocomputing and uncovering more efficient methods for capitalizing on student cultural propensities in the context of a robotics curriculum. Regarding creativity, studies evaluating advantages and disadvantages of different platforms, such as Alice (Caprari, Estier, & Siegwart, 2001), Scratch (Resnick et al., 2009), and LEGO (Lau, Tan, Erwin, & Petrovic, 1999; Lund & Pagliarini, 1998), would be valuable in helping educators decide which platform is most appropriate for particular reasons. It is also noted that research practices tend to conduct surveys on students only immediately after an intervention, such as at a camp or an educational program. However, conducting longitudinal studies that track the future decisions of career paths by individual participants would allow researchers to evaluate whether or not there are long-lasting effects. Furthermore, allowing participants time to reflect on the learning experiences would also provide feedback on what specific components of an educational program had an enduring influence on students' perceptions and interests. In addition, although some studies have explored the effectiveness of robotics on students' learning outcomes, more studies are needed to evaluate the relative effectiveness of robotics in comparison to other intervention-based instructional methods. Such studies will validate the use of resources in introducing robotics in K–12 spaces. Finally, as Streveler and Menekse (2017) suggested, more fine-grained studies are needed to understand the role of educational robotics across contexts, activities, and disciplines for which they are best suited, and for what kind of students.

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Appendix B: Classification of the reviewed studies based on the specific themes

Theme 1:
General Effectiveness of Educational Robotics

Altun, Korkmaz, Ozkaya, & Usta (2013)	Lessons learned from robot-in-class projects using LEGO nxt and some recommendations
Avsec, Rihtarsic, & Kocijancic (2014)	A predictive study of learner attitudes toward open learning in a robotics class
Barger, Gilbert, & Boyett (2011)	Best practices for student robotic camps
Bers, Flannery, Kazakoff, & Sullivan (2014)	Computational thinking and tinkering: Exploration of an early childhood robotics curriculum
Casad, & Jawaharlal (2012)	Learning through guided discovery: An engaging approach to K–12 STEM education
Chalmers (2013)	Learning with first LEGO league
Chambers, Carbonaro, & Murray (2008)	Developing conceptual understanding of mechanical advantage through the use of LEGO robotic technology
Chen, Shen, Barth-Cohen, Jiang, Huang, & Eltoukhy (2017)	Assessing elementary students' computational thinking in everyday reasoning and robotics programming
Chin, Hong, & Chen (2014)	Impact of using an educational robot-based learning system on students' motivation in elementary education
Chung, Oh, Shim, & Sastry (2011)	Toward robotic sensor webs: Algorithms, systems, and experiments.
Di Lieto, Inguaggiato, Castro, Cecchi, Cioni, Dell'Omo, ... Dario (2017)	Educational robotics intervention on executive functions in preschool children: A pilot study
Erdogan, Sencer Corlu, & Capraro (2013)	Defining innovation literacy: Do robotics programs help students develop innovation literacy skills?
Ganesh, Thieken, Baker, Krause, Roberts, Elser, & Kurpius (2010)	Learning through engineering design and practice: Implementation and impact of a middle school engineering-education program
Hussain, Lindh, & Shukur (2006)	The effect of LEGO training on pupils' school performance in mathematics, problem solving ability and attitude: Swedish data
Jipson, Gülgöz, & Gelman (2016)	Parent–child conversations regarding the ontological status of a robotic dog
Jordan (2014)	Exploring how design critique processes shape fifth graders' peer interaction in collaborative engineering projects
Knop, Ziaeefard, Ribeiro, Page, Ficanha, Miller, & Mahmoudian (2017)	A human-interactive robotic program for middle school STEM education
Kucuk, & Sisman (2017)	Behavioral patterns of elementary students and teachers in one-to-one robotics instruction
Lakanen, Isomöttönen, & Lappalainen (2012)	Life two years after a game programming course: Longitudinal viewpoints on K–12 outreach
Laut, Kapila, & Iskander (2013)	Exposing middle school students to robotics and engineering through LEGO and MATLAB
Leonard, Buss, Gamboa, Mitchell, Fashola, Hubert, et al. (2016)	Using robotics and game design to enhance children's self-efficacy, STEM attitudes, and computational thinking skills
Mac Iver, & Mac Iver (2014)	"Stemming" the swell of absenteeism in urban middle grade schools: Impacts of a summer robotics program
Matkins, McLaughlin, Brown, Hardinge, West, Stiegler, & Jenne (2008)	Evaluating a comprehensive middle school outreach program—The results
Menekse, Higashi, Schunn, & Baehr (2017)	The role of robotics teams' collaboration quality on team performance in a robotics tournament
Mills, Chandra, & Park (2013)	The architecture of children's use of language and tools when problem solving collaboratively with robotics
Montironi, Eliahu, & Cheng (2015)	A robotics-based 3D modeling curriculum for K–12 education
Morishita, & Yabuta (2007)	High school educational program using a simple and compact stereo vision robot
Mosley, Ardito, & Scollins (2016)	Robotic cooperative learning promotes student stem interest
Nabeel, Latifee, Naqi, Aqeel, Arshad, & Khurram (2017)	Robotics education methodology for K–12 students for enhancing skill sets prior to entering university
Okita (2014)	The relative merits of transparency: Investigating situations that support the use of robotics in developing student learning adaptability across virtual and physical computing platforms
Ortiz (2010)	Fifth grade students' understanding of ratio and proportion in an engineering robotics program
Osborne, Thomas, & Forbes (2010)	Teaching with robots: A service-learning approach to mentor training
Peleg, & Baram-Tsabari (2017)	Learning robotics in a science museum theatre play: Investigation of learning outcomes, contexts and experiences
Rosen, Hendricks, Robinson, & Sonnenberg-Klein (2013)	First LEGO league participation: Perceptions of minority student participants and their FLL coaches
Rursch, Luse, & Jacobson (2010)	IT-adventures: A program to spark IT interest in high school students using inquiry-based learning with cyber defense, game design, and robotics
Ryder, Pegg, & Wood (2012)	A project-based engineering and leadership workshop for high school students
Sahin, Ayar, & Adiguzel (2014)	STEM-related after-school program activities and associated outcomes on student learning
Shatz, Pieloch, & Shamieh (2016)	Robotics competition and family science fair for grades 4–8 sponsored by the Latino-STEM alliance
Shih, Chen, Wang, & Chen (2013)	The exploration of applying LEGO NXT in the situated science and technology learning
Silk, Higashi, & Schunn (2011)	Resources for robot competition success: Assessing math use in grade-school-level engineering design
Sivilotti, & Laugel (2008)	Scratching the surface of advanced topics in software engineering: A workshop module for middle school students
Stansbury, & Behi (2012)	Inspiring interest in STEM through summer robotics camp
Taban, Acar, Ismailm Ayhan (2005)	Teaching basic engineering concepts in K–12 environments using LEGO bricks and robotics
Williams, Ma, Prejean, Ford, & Lai (2007)	Acquisition of physics content knowledge and scientific inquiry skills in a robotics summer camp
Zahn, Pea, Hesse, & Rosen (2010)	Comparing simple and advanced video tools as supports for complex collaborative design processes

Theme 2:
Learning and Transfer Skills

Aslam et al. (2014)	Passive maple-seed robotic fliers for education, research and entrepreneurship
Ayar (2015)	First-hand experience with engineering design and career interest in engineering: An informal stem education case study
Ayar, Yalvac, Uğurdağ, & Şahin (2013)	A robotics summer camp for high school students: Pipelines activities promoting careers in engineering fields
Barker, & Ansorge (2007)	Robotics as means to increase achievement scores in an informal learning environment
Feaster, Segars, Wahba, & Hallstrom (2011)	Teaching CS unplugged in the high school (with limited success)
Ganesh, & Thieken (2010)	Designing and implementing chain reactions: A study of seventh-grade students' knowledge of electrical circuits
He, Saad, Reed, Hannigan, & Strauser (2008)	Information technology education for K–12 students and teachers: From sensor network to comprehensive and customized web interaction
He, Zubarriain, & Kumia (2015)	Integrating robotics education in pre-college engineering program
Jackson, Mentzer, & Kramer-Bottiglio (2018)	Intersecting self-efficacy and interest: Exploring the impact of soft robot design experiences on engineering perceptions
Kazakoff, & Bers (2014)	Put your robot in, put your robot out: Sequencing through programming robots in early childhood
Koh, Repenning, Nickerson, Endo, & Motter (2013)	Will it stick? Exploring the sustainability of computational thinking education through game design
Krishnamoorthy, & Kapila (2016)	Using a visual programming environment and custom robots to learn c programming and K–12 STEM concepts
Lawanto et al. (2013)	Pattern of task interpretation and self-regulated learning strategies of high school students and college freshmen during an engineering design project
Lindh, & Holgersson (2007)	Does LEGO training stimulate pupils' ability to solve logical problems?
McGrath, Lowes, Lin, Sayres, Hotaling, & Stolkin (2008)	Build IT: Building middle and high school students' understanding of engineering, science and IT through underwater robotics
McKay, Lowes, Tirhali, & Camins (2015)	Student learning of STEM concepts using a challenge-based robotics curriculum
Nugent, Barker, Grandgenett, & Adamchuk (2009)	The use of digital manipulatives in K–12: Robotics, GPS/GIS and programming
Nugent, Barker, Grandgenett, & Adamchuk (2010)	Impact of robotics and geospatial technology interventions on youth STEM learning and attitudes
Oliveira, Nicoletti, & del Val Cura (2014)	Quantitative correlation between ability to compute and student performance in a primary school
Phalke, Biller, Lysecky, & Harris (2009)	Non-expert construction of customized embedded systems to enhance STEM curricula
Rieksts, & Blank, (2008)	Mars rovers in middle school
Robinson, & Stewardson (2012)	Exciting students through VEX robotic competitions
Sánchez-Ruíz, & Jamba (2008)	FunFonts: Introducing 4th and 5th graders to programming using Squeak
Shankar, Ploger, emeth, & Hecht (2013)	Robotics: Enhancing pre-college mathematics learning with real world examples
Silk, Higashi, & Schunn (2011)	Resources for robot competition success: Assessing math use in grade-school-level engineering design
Suescun-Florez, Cain, Kapila, & Iskander (2013)	Bringing soil mechanics to elementary schools
Sullivan (2008)	Robotics and science literacy: Thinking skills, science process skills and systems understanding
Taub, Armoni, & Ben-Ari (2012)	CS unplugged and middle-school students' views, attitudes, and intentions regarding CS
Touretzky, Marghitu, Ludi, Bernstein, & Ni (2013)	Accelerating K–12 computational thinking using scaffolding, staging, and abstraction
Williams, Igel, Poveda, Kapila, & Iskander (2012)	Enriching K–12 science and mathematics education using LEGO
Williams, Kapila, & Iskander (2011)	Enriching K–12 science education using LEGO
Ziaeefard, Page, Knop, Ribeiro, Miller, Rastgaar, & Mahmoudian (2017)	GUPPIE program—A hands-on STEM learning experience for middle school students

Theme 3:
Creativity and Motivation

Ayar (2015)	First-hand experience with engineering design and career interest in engineering: An informal STEM education case study
Barco, Albo-Canals, & Garriga (2014)	Engagement based on a customization of an iPod-LEGO robot for a long-term interaction for an educational purpose
Bernstein & Crowley (2008)	Searching for signs of intelligent life: An investigation of young children's beliefs about intelligence and animacy
Bers, Flannery, Kazakoff, & Sullivan (2014)	Computational thinking and tinkering: Exploration of an early childhood robotics curriculum
Crawford, White, Muller, Petrosino, Talley, & Wood (2012)	Foundations and effectiveness of an after-school engineering program for middle school students
Cuellar et al. (2014)	Robotics education initiative for analyzing learning and child-parent interaction
De Michele, Demo, & Siega (2008)	Piedmont schoolnet for a K–12 mini-robots [rogramming project: Experiences in primary schools
Doerschuk, Liu, & Mann (2011)	Inspired high school computing academies
Eguchi, & Uribe (2012)	Is educational robotics for everyone? A case study of a 4th-grade educational robotics unit
Giannakos, Jaccheri, & Proto (2013)	Teaching computer science to young children through creativity: Lessons learned from the case of Norway

Hamner, & Cross (2013)	Arts & bots: Techniques for distributing a steam robotics program through K–12 classrooms
Hwang, & Wu (2014)	A case study of collaboration with multi-robots and its effect on children's interaction
Igel, Poveda, Kapila, &Iskander (2011)	Enriching K–12 math education using LEGO
Jackson, Mentzer, & Kramer-Bottiglio (2018)	Intersecting self-efficacy and interest: Exploring the impact of soft robot design experiences on engineering perceptions
Jordan, & McDaniel Jr (2014)	Managing uncertainty during collaborative problem solving in elementary school teams: The role of peer influence in robotics engineering activity
Kafai, Searle, Martinez, & Brayboy (2014)	Ethnocomputing with electronic textiles: Culturally responsive open design to broaden participation in computing in American Indian youth and communities
Kaloti-Hallak, Armoni, & Ben-Ari (2015)	Students' attitudes and motivation during robotics activities
Knop, Ziaeefard, Ribeiro, Page, Ficanha, Miller, & Mahmoudian (2017)	A human-interactive robotic program for middle school STEM education
Krishnamoorthy, & Kapila (2016)	Using a visual programming environment and custom robots to learn c programming and K–12 STEM concepts
Liu, Liu, Wang, Chen, & Su (2012)	Applying tangible story avatars to enhance children's Collaborative storytelling
Liu, Navarrete, & Wivagg (2014)	Potentials of mobile technology for K–12 education: An investigation of iPod touch use for English language learners in the United States
Master, Cheryan, Moscatelli, & Meltzoff (2017)	Programming experience promotes higher STEM motivation among first-grade girls
McDonald, & Howell (2012)	Watching, creating and achieving: Creative technologies as a conduit for learning in the early years
McGrath, Lowes, Lin, Sayres, Hotaling, & Stolkin (2008)	Build IT: Building middle and high school students' understanding of engineering, science and IT through underwater robotics
Menekse, Higashi, Schunn, & Baehr (2017)	The role of robotics teams' collaboration quality on team performance in a robotics tournament
Muldoon, Phamdy, Grand, Kapila, & Iskander (2013)	Connecting cognitive domains of Bloom's taxonomy and robotics to promote learning in K–12 environment
Nemiro, Larriva, & Jawaharlal (2017)	Developing creative behavior in elementary school students with robotics
Ozis, Newley, & Kaya (2016)	First round evaluation of first tech challenge robotics club: Does it really prepare students for beyond college?
Powers, Leibbrandt, Luerssen, Lewis, & Lawson (2008)	Peta—A pedagogical embodied teaching agent
Puvirajah, Verma, & Webb (2012)	Examining the mediation of power in a collaborative community: Engaging in informal science as authentic practice
Robinson (2005)	Robotics-driven activities: Can they improve middle school science learning?
Robinson, & Stewardson (2012)	Exciting students through VEX robotic competitions.
Ruf, Mühling, & Hubwiese (2014)	Scratch vs. Karel—Impact on learning outcomes and motivation
Ruiz-del-Solar & Avilés (2004)	Robotics courses for children as a motivation tool: The chilean experience
Rusak, & Lim (2014)	Come code with codester: An educational app that teaches computer science to K–6 students
Ryder, Pegg, & Wood (2012)	A project-based engineering and leadership workshop for high school students
Seals, & Smith (2013)	Enhancing K–12 education with engineering outreach
Searle, Fields, Lui, & Kafai (2014)	Diversifying high school students' views about computing with electronic textiles
Sentance, & Schwiderski-Grosche (2012)	Challenge and creativity: Using .NET gadgeteer in schools
Shanahan, & Marghitu (2013)	Software engineering Java curriculum with Alice and cloud computing
Siraj, Kosa, & Olmstead (2012)	Weaving a tapestry: Creating a satellite workshop to support HS CS teachers in attracting and engaging students
Smith, Sutcliffe, & Sandvik (2014)	Code club: Bringing programming to UK primary schools through scratch
Stansbury, & Behi (2012)	Inspiring interest in STEM through summer robotics camp
Sullivan, & Wilson (2015)	Playful talk: Negotiating opportunities to learn in collaborative groups
Taban, Acar, Ismailm Ayhan (2005)	Teaching basic engineering concepts in K–12 environment using LEGO bricks and robotics
Tatsumi, Nakano, Tajitsu, Okumura, & Harada (2009)	Incorporating music into the study of algorithms and computer programming
Terry, Briggs, & Rivale (2011)	Work in progress: Gender impacts of relevant robotics curricula on high school students' engineering attitudes and interest
van Delden, & Yang (2014)	Robotics summer camps as a recruiting tool: A case study
Wagner, Gray, Corley, & Wolber (2013)	Using app inventor in a K–12 summer camp
Welch, & Huffman (2011)	The effect of robotics competitions on high school students' attitudes toward science
Werner, Denner, Bliesner, & Rex (2009)	Can middle-schoolers use storytelling Alice to make games? Results of a pilot study
Wyffels et al. (2014)	Starting from scratch: Experimenting with computer science in Flemish secondary education
Ziaeefard, Page, Knop, Ribeiro, Miller, Rastgaar, & Mahmoudian (2017)	GUPPIE program—A hands-on STEM learning experience for middle school students

Theme 4:
Diversity and Broadening Participation

Doerschuk et al. (2011)	Inspired high school computing academies
Dorsey, & Howard (2011)	Measuring the effectiveness of robotics activities in underserved K–12 communities outside the classroom
Erickson-Ludwig (2015)	A college lead informal learning engineering education program for school-aged youth
Frye, Nair, & Meyer (2016)	Evaluation of minigems 2015—Engineering summer camp for middle school girls
Gomoll, Hmelo-Silver, Šabanović, & Francisco (2016)	Dragons, ladybugs, and softballs: Girls' STEM engagement with human-centered robotics
Hulsey, Pence, & Hodges (2014)	Camp Cybergirls: Using a virtual world to introduce computing concepts to middle school girls
Mason, Cooper, & Comber (2011)	Girls get IT
Master, Cheryan, Moscatelli, & Meltzoff (2017)	Programming experience promotes higher STEM motivation among first-grade girls
McDonald, & Howell (2012)	Watching, creating and achieving: Creative technologies as a Conduit for learning in the early years
Ozis, Newley, & Kaya (2016)	First round evaluation of first tech challenge robotics club: Does it really prepare students for beyond college?
Rieksts, & Blank (2008)	Inspiring future IT professionals with Mars rovers
Rosen, & Newsome (2011)	Promoting diversity and public school success in first LEGO league state competitions
Shatz, Pieloch, & Shamieh (2016)	Robotics competition and family science fair for grades 4–8 sponsored by the Latino-STEM alliance
Siraj et al. (2012)	Weaving a tapestry: Creating a satellite workshop to support HS CS teachers in attracting and engaging students
Terry et al. (2011)	Work in progress: Gender impacts of relevant robotics curricula on high school students' engineering attitudes and interest
Zimmerman, Johnson, Wambsgans, & Fuentes (2011)	Why Latino high school students select computer science as a major: Analysis of a success story

Theme 5:
Teachers' Professional Development

Alimisis (2012)	Robotics in education & education in robotics: Shifting focus from technology to pedagogy
Aslam et al. (2014)	Passive maple-seed robotic fliers for education, research and entrepreneurship
Cejka, Rogers, & Portsmore (2006)	Kindergarten robotics: Using robotics to motivate math, science, and engineering literacy in elementary school
Chiou (2012)	Teaching technology using educational robotics
Cooper, Dann, & Harrison (2010)	A K–12 college partnership
Crawford, White, Muller, Petrosino, Talley, & Wood (2012)	Foundations and effectiveness of an after-school engineering program for middle school students
Curzon, McOwan, Plant, & Meagher (2014)	Introducing teachers to computational thinking using Unplugged storytelling
desJardins, & Martin (2013)	Maryland: The state of computer science education in Maryland high schools
Dodds, & Karp (2006)	The evolution of a computational outreach program to secondary school students
Doerschuk, Liu, & Mann (2007)	Pilot summer camps in computing for middle school girls: From organization through assessment
Dunn, Strader, & Pickard (2011)	Camps on a shoestring: How we survived a summer?
Erdogan, Sencer Corlu, & Capraro (2013)	Defining innovation literacy: Do robotics programs help students develop innovation literacy skills?
España, Builes, & Bedoya (2013)	Robotic kit teac^{2}h-ri for applications in education and research
Feaster, Ali, Zhai, & Hallstrom (2013)	Serious toys ii: Teaching networks, protocols, and algorithms
Ganesh, Thieken, Baker, Krause, Roberts, Elser,& Kurpius (2010)	Learning through engineering design and practice: Implementation and impact of a middle school engineering-education program
Goode, & Margolis (2011)	Exploring computer science: A case study of school reform
Guzdial, Ericson, Mcklin, & Engelman (2014)	Georgia computes! An intervention in a US state, with formal and informal education in a policy context
Harris, & Hofer (2011)	Technological pedagogical content knowledge (tpack) in action: A descriptive study of secondary teachers' curriculum-based, technology-related instructional planning
Imberman, Sturm, & Azhar (2014)	Computational thinking: Expanding the toolkit
Kay, & McKlin (2014)	The challenges of using a mooc to introduce "absolute beginners" to programming on specialized hardware
Laut, Kapila, & Iskander (2013)	Exposing middle school students to robotics and engineering through LEGO and MATLAB
Mills, Chandra, & Park (2013)	The architecture of children's use of language and tools when problem solving collaboratively with robotics
Myketiak, Curzon, Black, McOwan, & Meagher (2012)	Cs4fn: A flexible model for computer science outreach
Pittí, Curto, Moreno, & Rodríguez (2013)	Resources and features of robotics learning environments (rles) in Spain and Latin America
Sabin, Higgs, Riabov, & Moreira (2005)	Designing and running a pre-college computing course
Seiter, & Foreman (2013)	Modeling the learning progressions of computational thinking of primary grade students
Spradling, Linville, Rogers, & Clark (2015)	Are MOOCs an appropriate pedagogy for training K–12 teachers' computer science concepts?
Stubbs, & Yanco (2009)	Stream: A workshop on the use of robotics in K–12 stem education