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Robotic Construction Kits as Computational Manipulatives for Learning in the STEM Disciplines

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Abstract

This article presents a systematic review of research related to the use of robotics construction kits (RCKs) in P–12 learning in the STEM disciplines for typically developing children. The purpose of this review is to configure primarily qualitative and mixed methods findings from studies meeting our selection and quality criterion to answer the review question: How do robotic construction kits function as computational manipulatives in P–12 STEM education? Our synthesis of the literature has resulted in four key insights that are new to the field. First, RCKs have a unique double application: They may be used for direct instruction in robotics (first-order uses) or as analogical tools for learning in other domains (second-order uses). Second, RCKs make possible additional routes to learning through the provision of immediate feedback and the dual modes of representation unique to RCKs. Third, RCKs support a computational thinking learning progression beginning with a lower anchor of sequencing and finishing with a high anchor of systems thinking. And fourth, RCKs support evolving problem-solving abilities along a continuum, ranging from trial and error to heuristic methods associated with robotics study. Furthermore, our synthesis provides insight into the second-order (analogical) uses of RCKs as computational manipulatives in the disciplines of physics and biology. Implications for practice and directions for future research are discussed. (Keywords: computational manipulatives, constructionism, computational thinking, problem solving, robotics, STEM)

This article presents a systematic review (Gough & Thomas, 2012) of robotic construction kits (RCKs) as computational manipulatives for P–12 learning in the STEM disciplines for typically developing children. The purpose of this review is to configure primarily qualitative and mixed methods findings from studies meeting our selection and quality criterion to answer the review question: How do robotic construction kits function as computational manipulatives in P–12 STEM education? This approach differs from systematic reviews that aggregate quantitative data only to determine the effectiveness of an intervention. Barreto and Benitti (2012) found generally positive effects in their systematic review of quantitative robotics studies. In contrast, this configurative review (Gough, Oliver, & Thomas, 2012) examines qualitative, mixed methods, and quasi-experimental studies to identify emergent themes, models, and potential learning progressions associated with the use of RCKs as computational manipulatives in the P–12 classroom (Thomas, Harden, & Newman, 2012).

Manipulatives are physical or virtual entities that scaffold student understanding in a given domain. For example, physical manipulatives such as Cuisenaire rods are used in early math learning to help young children develop conceptual understanding in mathematics (Manches & O'Malley, 2012). The rods are designed in such a way (color, shape, size) as to be imbued with specific relational meanings. Such designed manipulatives allow a child to build a bridge of understanding from the conceptual relationships embodied in the manipulative to the target domain. Manipulatives are concrete referents to abstract concepts. Interaction with manipulatives engenders analogical

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reasoning and embodied cognition (Fishkin, 2004; Manches & O'Malley, 2012). Weiskopf (2010) defines *embodied cognition* as "cognitive capacities are shaped and structured by the bodily capacities of a creature, including the sensorimotor capacities that make possible its basic interactions with the world" (p. 295). The theoretical basis for embodied cognition is provided by Barsalou's (2003) situated simulation theory. In this formulation, cognition is not characterized by what Barsalou terms "amodal semantic knowledge," but, rather, by modal recall (simulation) of experiences and actions on a sensorimotor level. Barsalou argues that

> When the conceptual system represents an object's visual properties, it uses representations in the visual system; when it represents the actions performed on an object, it uses motor representations. The claim is not that modal reenactments constitute the sole form of conceptual representation . . . The claim is simply that modal reenactments are an important and widely utilized form of representation. (p. 521)

Embodied cognition is enabled by manipulatives through the provision of an additional channel during learning, activating real-world knowledge, and improving memory through physical action (McNeil & Jarvin, 2007).

Computational (or digital) manipulatives are manipulatives that have on-board computing capabilities, such as LEGO Mindstorms robotic kits, programmable beads, and other toys with embedded computers (Resnick et al., 1998). Taking the LEGO Mindstorms kit as an example, children both build and program LEGO-based robots to interact with their environment. Through the use of actuators (motors) and sensors (e.g., light, touch, motion, distance, and rotation sensors), students program the robotic device to measure a variable in the environment, which then triggers a specific programmed response from the robotic device. A typical robotics challenge activity will have students working in teams to build and program a robotic car to utilize a light sensor to follow a colored path on the floor. In actual STEM fields, prototypes and models are constructed to test ideas and designs. RCKs may be used to engage students in such authentic STEM activities.

Computational manipulatives are different from traditional manipulatives in that they may be used as either (a) a direct (concrete) conceptual representation of a domain (robotics) or (b) an analogical representation of concepts in a domain (e.g., biological systems). In the first use, as a direct representation, the computational manipulative promotes both analogical and embodied cognition (Papert, 1993). In the context of the LOGO programming language, Papert found that children used knowledge of their own body movements to successfully program the LOGO turtle's movements on the screen. Moreover, in our work we have found a similar phenomenon in the context of student learning with RCKs. In our study, students performed physical motions to simulate the movement of the robotic device along a proposed path. As they did this, they actively considered the programming elements needed to computationally create the same movement (Sullivan & Lin, 2012). In both cases, Barsalou's (2003) notion of situated simulation is at work. Therefore, analogical and embodied cognition in the realm of RCKs refers to students' use of internalized, modal representations of their own movement as a basis for reasoning about how to program the movement of the robotic device. In addition to analogical and embodied cognition, and due to the immediate feedback made possible by the computational nature of robotics materials, RCKs also introduce additional modes of learning, including reflection, discussion, and iterative problem-solving cycles (Papert, 1993; Sullivan, 2011).

In the second-order use as an analogical representation, the computational manipulative also promotes learning through analogical reasoning, embodied cognition, reflection, discussion, and problem solving. In order to use RCKs as a computational manipulative in the traditional sense, a teacher or student must first identify the computational (functional) aspects of the to-be-learned concepts in the target domain. Then the teacher or student may model these concepts with the robotics materials. The designed robotics device acts as an analogical bridge to concepts in the target domain. An example of this may be seen in Braitenberg Vehicles. Braitenberg (1986) developed a view of "certain structures within animal brains that seemed to be interpretable as pieces of computing machinery because of their simplicity or regularity" (p. 1). From this insight, he created robotic vehicles that helped him think more deeply about the mechanisms underlying sensory and cognitive aspects of animal intelligence. The systems he built were simple structures that supported cognitive elements (as simulated by the microcomputer), perceptual elements (as simulated by sensing devices), and locomotion elements (as simulated by motor and wheels).

RCKs as computational manipulatives, therefore, function in one of two capacities: first as manipulatives for directly learning about robotics (first-order uses) and second, as a manipulative for understanding concepts in a target domain from a computational perspective (second-order uses). In order to clearly distinguish between first- and second-order uses of RCKs, it is necessary to establish the disciplinary boundaries of robotics practice.

Disciplinary Practices of Robotics

Engineering design and computer programming comprise the fundamental practices of robotics activity. The Next Generation Science Standards (NGSS, 2013), built on the Framework for K–12 Science Education (National Research Council [NRC], 2012), provide a relevant definition of the activities and practices that make up the engineering design process at the P–12 level. In the NGSS conceptualization, engineering design is reframed not just as an example of applied science, but as an important scientific activity in its own right: an activity that is parallel, in practice, to that of science inquiry. Indeed, the NGSS and the Framework for K–12 articulate eight core disciplinary practices that are common to both science inquiry and engineering design as follows:

1. Asking questions (for science) and defining problems (for engineering).
2. Developing and using models.
3. Planning and carrying out investigations.
4. Analyzing and interpreting data.
5. Using mathematics and computational thinking.
6. Constructing explanations (for science) and designing solutions (for engineering).
7. Engaging in argument from evidence.
8. Obtaining, evaluating, and communicating information (NRC, 2012, p. 46).

The engineering design process is an empirically documented aspect of robotics activity that includes, but is not limited to, defining the problem, designing and building a robotic device, testing the device, diagnosing and troubleshooting problems, making revisions, and making trade-offs (Bers, 2007; Sullivan, 2011). Engineering design is also used as way to teach (a) general problem-solving skills and (b) science process skills (an important part of science literacy).

Robotics also entails the learning of computer programming concepts such as iteration, input/process/output, and control structures (procedural flow) (Sullivan & Lin, 2012). Importantly, it also includes certain modes of thinking and habits of mind characteristic of computer programmers, known as computational thinking (Wing, 2006). A definition of computational thinking at the P–12 level was developed by a joint working group of the International Society for Technology in Education and the Computer Science Teachers Association (ISTE/CSTA, 2011) and was made available on their website as follows:

Computational thinking (CT) is a problem-solving process that includes (but is not limited to) the following characteristics:

- Formulating problems in a way that enables us to use a computer and other tools to help solve them.
- Logically organizing and analyzing data.
- Representing data through abstractions such as models and simulations.
- Automating solutions through algorithmic thinking (a series of ordered steps).

- Identifying, analyzing, and implementing possible solutions with the goal of achieving the most efficient and effective combination of steps and resources.
- Generalizing and transferring this problem solving process to a wide variety of problems.

Computational thinking includes activities that support the practice of effective computer programming, including problem solving (e.g., algorithmic development, heuristic development, organization, planning, search), abstraction (creating a new representation of a problem), and design (creating models and simulations). Research studies related to RCKs as first-order computational manipulatives may focus on disciplinary practices that make up robotics study: the engineering design process, computer science concepts, and engaging in computational thinking. Research studies related to RCKs as second-order computational manipulatives include studies that use robotics to model scientific phenomena in domains other than robotics, such as physics and biology.

Importantly, each of these uses of RCKs introduces additional modes of learning through its computational nature. To consider how these modes of learning are enabled, it is useful to reflect upon the learning theory that guided the development of the most popular of educational robotics systems: the LEGO-produced programmable brick. Resnick and Martin (1991), students of Papert at the Massachusetts Institute of Technology, developed this technology based on the tenets of Papert's (1991, 1993) theory of learning, which he calls *constructionism*.

Constructionism

Papert (1991), a student of Piaget, has stated that the theory of constructionism shares Piaget's (1981) basic view that human cognitive development and learning consists of "building knowledge structures" (p. 1) through interaction with the natural and designed environment. However, constructionist theory diverges from Piaget's constructivism in relation to the hierarchy of stages: most notably the third and fourth stages. Constructionists do not privilege abstract thinking as the pinnacle of cognitive development. Rather, they argue that high levels of understanding may also be reached through proximal interactions with concrete objects (Turkle & Papert, 1991; Resnick, 2004). It is this belief that underlies the design of computational manipulatives as learning objects.

Proximal interactions with computational manipulatives enable several important learning activities to take place. First, as an externality, children are able to imagine themselves in place of the computational manipulative in order to reason about how to program its movement (Papert, 1993). In an interesting way, the child's own body becomes a manipulative in the traditional sense, acting as an analog to the computational device. Second, as an externality, the computational manipulative serves to spark discussion among students that leads to insights and learning (Sullivan, 2011). Third, when students encounter programming results that are inconsistent with their expectations, which is common to robotics activities, students are spurred to develop explanations of why this is so, which improves causal reasoning (Legare, Gelman, & Wellman, 2010). Fourth, when children write and execute a program for a computational manipulative, they receive immediate feedback on the efficacy of their programs from the device itself. This immediate feedback initiates a troubleshooting cycle that involves discussion and diagnosis of the problem, including reflection on the current state of the program, analysis of potential error-causing elements, and the creation of plans for remedying the problem or gaining more information about the problem (Sullivan, 2011).

In terms of computational manipulatives, the relevant tenets of the constructionist learning theory are that (a) learning occurs through embodiment; (b) learning occurs through collaborative dialogue spurred by the external nature of the device; and (c) learning occurs through the reflection, explanation, and problem-solving activity that is promulgated by the immediate feedback mechanism of a computational manipulative. While other types of manipulatives may enable embodiment, collaborative dialogue, and explanation, the stimulation of reflection and problem-solving activity through immediate feedback may be unique to computational manipulatives.

Having differentiated the first-order (direct representation) and second-order (analogical representation) uses of RCKs as computational manipulatives and established the learning activities they enable, we now turn to an examination of research related to RCKs in P–12 STEM learning.

P–12 STEM Learning With RCKs

A literature search of empirical studies devoted to P–12 STEM learning with RCKs was conducted in six electronic databases: Academic Search Premiere, the ACM Digital Archive, Education Journals, JSTOR, PsychInfo, and Social Science Abstracts. These databases were selected (with the exception of the ACM Digital Archive) because they are commonly used databases in education that archive articles from a number of education and educational psychology journals. Research related to P–12 STEM learning with RCKs is most likely to be published in such journals. The ACM digital archive was included because some computer science researchers have an interest in computer science education and perform educational research. We also searched Google Scholar in order to find articles that may have been published in international journals that are not indexed in U.S databases. The inclusive dates for the literature search were 1999–2014, a 15-year period. We chose this time period as it coincides with the growth and popularity of the Mindstorms Robotics Kits produced by LEGO.

The literature search consisted of pairing the keyword "robotics" in a logical "AND" search with each of the following keywords in turn: computational thinking, constructionism, education, manipulatives, Mindstorms, modeling, P–12, problem solving, school, science literacy, STEM learning, mathematics, science, technology, and engineering. For the technology and engineering keywords, the keyword education was added to eliminate studies about the actual design and engineering of robots themselves. We included this large number of keywords to cast as broad a net as possible in identifying articles dealing with STEM learning with robotics. As with many technologies, robots can be used in multiple domains and in multiple ways. Thus, we reasoned, the use of a large number of keywords in a logical AND search with the primary keyword of "robotics" would allow us to identify all relevant articles. Table 1 summarizes the main search parameters.

The searches resulted in 922 hits, and in total 133 unique articles were found on the topic of robotics in P–12 education. However, 83 of these articles did not specifically address P–12 student STEM learning outcomes (content or process). Rather, these 83 articles focused on research related to (a) content areas other than STEM (e.g., literacy); (b) student responses to robotic tutors, pets, and/or animals; (c) learning with robotics for children with disabilities or injuries; (d) use of robotics for creating specific types of learning environments (e.g., mixed reality); (e) interest in and attitudes toward STEM and/or robotics; (f) teacher professional development, curriculum development and instructional strategies; and (g) descriptions of design and development projects related to creating

Table 1. Literature Search Summary

Databases	Search Terms Used Within Each Database
Academic Search Premiere	computational thinking AND robotics
ACM Digital Archive	constructionism AND robotics
Education Journals	education AND robotics
Google Scholar	engineering AND robotics AND education
JSTOR	mathematics AND robotics
PsychInfo	Mindstorms AND robotics
Social Science Abstracts	manipulatives AND robotics
	modeling AND robotics
	P12 AND robotics
	problem solving AND robotics
	school AND robotics
	science AND robotics
	science literacy AND robotics
	STEM learning AND robotics
	technology AND robotics AND education

robotics learning tools or environments. While each of these areas may have an impact on student learning, the goal here is to examine the research on specific STEM learning outcomes for typically developing children that are related to the use of RCKs as first- or second-order computational manipulatives. Therefore, these 83 studies that were not specifically focused on student STEM learning outcomes were excluded from the review. Nine dissertations devoted to STEM learning with RCKs were also excluded because they were unpublished and had not undergone a rigorous process of peer review.

This left 41 studies that focused specifically on P–12 STEM learning with RCKs for typically developing children. A significant number of these studies employed qualitative research methods. Goals of qualitative research into student learning with RCKs include identifying factors and processes that influence learning with these devices and developing explanations for how learning with these devices occurs in certain settings. In order to systematically evaluate the trustworthiness of the data collected in these qualitative studies, a rubric was developed (Harden & Gough, 2012). Our trustworthiness of data in qualitative studies rubric (Table 2) was created based on the work of four experts: Erickson (1986), Maxwell (1992), Morrow (2005), and Bredo (2006). Erickson and Maxwell both provide clear guidance on how one may evaluate the validity (credibility) and reliability (dependability) of qualitative data. Morrow provides guidance on identifying the researcher stance in relation to truth claims based on the methods employed, and Bredo provides the philosophical, intellectual histories of each researcher stance. The researcher stance that is relevant to the work reviewed here is postpositivist. Postpositivist researchers adhere to the belief that all experience is subjective in nature. Therefore, postpositivist researchers attempt to minimize their own bias,

Table 2. Trustworthiness of Data in Qualitative Studies Rubric

Credibility of the Data	Strong	Fair	Weak
Description (correspondence of data to observable reality)	Complete description of setting and participants. Data are presented so that others would observe the same if in the setting.	Adequate description of setting and participants. Data are presented so that others would observe much of the same if in the setting.	Inadequate description of setting and participants.
Interpretation (correspondence of findings to the meanings made by the participants themselves)	Participant checks and/or peer debriefers are used to confirm the participants' meanings.	Interviews with participants and/or peer debriefers are used to identify participants' meanings.	No data are collected on participants' meanings.
Amount of data (enough data have been collected so that collection of new data would not add to meaning)	Complete saturation of data (prolonged engagement with/observation of participants).	Sufficient amounts of data have been collected (adequate engagement with/observation of participants).	Insufficient amounts of data have been collected (adequate engagement with/observation of participants).
Theoretical (the interpretation of the data results in an explanation of the patterns observed).	Strong theoretical underpinning for the results that has interpretive value.	Sufficient theoretical underpinning for the results that has interpretive value.	Insufficient or no theoretical underpinning for the results.
Dependability of the data			
Interrater reliability	Interrater reliability is provided for tallied categories using a method that partials out chance (Krippendorf or kappa)	Simple interrater reliability is provided for tallied categories.	No interrater reliability is provided for tallied categories.
Systematic rigor of fieldwork procedures (process through which findings are derived should be explicit and repeatable as much as possible)	Complete description of research activities and practices. Audit trail is provided.	Adequate description of research activities and practices.	Inadequate description of research activities and practices.
Triangulation (consistency of findings across methods and data sources)	A full range of data is collected from multiple sources.	An adequate range of data is collected from multiple sources.	An inadequate range of data is collected from multiple sources.

attempt to understand meaning from the participant perspective, and do not attempt to generalize beyond the research setting and participants in question. However, postpositivist qualitative research may be transferable (Morrow, 2005) in the sense that under similar circumstances, with a similar group of students, similar learning outcomes may accrue. We applied our trustworthiness of data in qualitative studies rubric to the qualitative articles identified through the literature search.

Of the 41 relevant studies, 20 were excluded due to weak research methods. These weaknesses included (a) insufficient data; (b) lack of interrater reliability; (c) lack of triangulation; (d) failure to address alternative explanations of the results; (e) lack of systematic rigor of field-work procedures (especially regarding data analysis); and/or (f) insufficient or no articulated theoretical underpinning with which to explain the results. These results were obtained through a close reading and rubric review of each of the studies by both the first and second authors. We achieved fidelity through discussion and comparison of the results of our individual reviews. The remaining 21 articles were of sufficient research quality to be considered for inclusion in this review.

The next step in the review was to classify the remaining articles as related to the notion of first- and second-order uses of computational manipulatives. Of the 21 articles included that met selection and quality criteria, 15 report on research related to RCKs as first-order computational manipulatives, four focus on RCKs as second-order computational manipulatives, and two studies report research related to both uses.

In the next section, we present a synthesis of the research on RCKs as first-order computational manipulatives focusing on three interrelated facets: (a) computational thinking, (b) problem solving, and (c) computer programming. Note that although computational thinking includes problem solving (usually a specific form that allows some problems to be solved with a computer), we found enough results on the development of general problem-solving abilities to merit its own section, separate from computational thinking. We then follow this with a presentation of our synthesis of the five studies that focus on second-order uses of robotics. Table A1 in the Appendix provides a summary of each study included in this configured review.

Results

First-Order Uses of RCKs as Computational Manipulatives

Computational thinking. Research related to the use of robotics as first-order computational manipulatives has focused on aspects of computational thinking that are afforded by the design of the materials including sequencing, reasoning, problem solving, and systems understanding. From this research, it is possible to discern a potential learning progression for students in studying robotics. Learning progressions are typically developed as a way to aid the instruction and assessment of student's science concepts (Duncan & Hmelo-Silver, 2009; Stevens, Delgado, & Krajcik, 2009). They include an upper anchor and a lower anchor. The upper anchor reflects where students need to be, as defined by the field or standards, while the lower anchor reflects where students typically start (Duncan & Hmelo-Silver, 2009). Learning progressions may consist of multiple interrelated construct maps, each of which measures progress in a specific concept (Krajcik, 2011). Learning progressions are developed using empirical data derived from longitudinal or cross-sectional studies, by an analysis of existing research, by an analysis of the domain, or through a combination of these methods (Duncan & Hmelo-Silver, 2009). Shea and Duncan (2013) argue that learning progressions "embody a developmental approach to learning by describing hypothetical paths that students might take as they develop progressively more sophisticated ways of reasoning about concepts and practices in a domain over extended periods of time" (p. 8).

The analysis of existing research reported in this section arguably supports a computational thinking learning progression in the robotics domain that begins with sequencing abilities, advances to reasoning abilities (causal inference and conditional reasoning), and results in improved systems understanding; all of which is aided by problem solving activity. Figure 1 provides a diagram of this proposed learning progression, offered here as an advanced organizer for reading the synthesis and critique of research below.

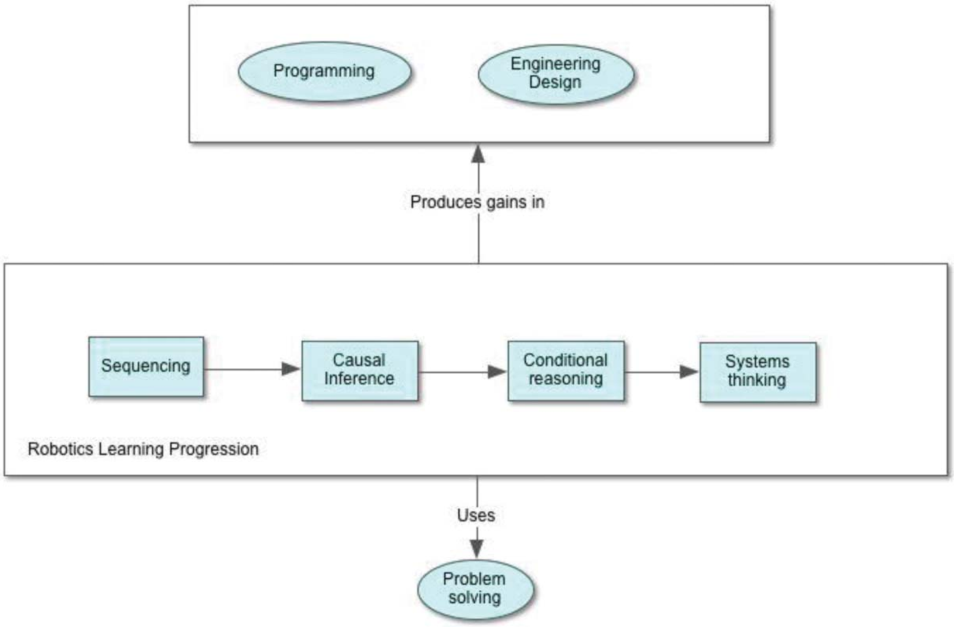

Figure 1. Configurative synthesis of learning with RCKs.

Sequencing ability. Sequencing refers to the ability to put items in a specific order. Sequencing abilities are foundational to learning to program a computer (Pea & Kurland, 1984; Pena & Tirre, 1992). Sequencing forms the lower anchor (starting point) of the proposed robotics learning progression. Preschool and kindergarten age children's sequencing ability has been shown to significantly improve when they are engaged in developmentally appropriate robotics programming activity (Bers, 2007; Kazakoff & Bers, 2012; Kazakoff, Sullivan, & Bers, 2013). These studies offer very promising results. However, it is not possible to put full faith in these results due to the low numbers of participants involved in these quantitative studies. Replication studies with larger numbers of participants would improve confidence in these findings.

Reasoning ability. Sequencing entails comparative reasoning. In order to accurately create a sequence, for example, in a seriation task, children must be able to compare the objects to be ordered along a specific, relevant dimension (Piaget & Inhelder, 1969/2000). In a robotics context, comparative reasoning is aided by immediate, concrete feedback from the programmed object itself. Children are able to compare the movement of the robotic device (a concrete representation) with the intended movement of the device as programmed on a computer screen or onboard display (an abstract representation). Discrepancies in expected movement prompts a child to reflect on the relationship of the dual representations and develop some hypotheses about why the expected movement was not observed (Sullivan, 2008). This hypothesis generation activity is an example of causal inference (Jonassen & Ionas, 2008). The activity of engaging in causal inference as an aspect of causal reasoning is an outcome of both the immediate feedback mechanism and the affordance of dual representations of a phenomenon; together, these elements produce a unique quality of learning with computational manipulatives. Moreover, causal reasoning is a step on a learning path toward greater systems understanding, specifically regarding functional relations among parts of the system.

Causal reasoning. Mioduser, Levy, and Talis (2009) found that kindergarten children are able to engage in inferential causal reasoning when working with simple robotics programs. In a small microgenetic case study, they asked six young students to explain the movement of an observed robot. For simple programs, the children were able to abstract a rule for the behavior (e.g., it stops when it gets to the edge). However, as the programs became more complex, for example, involving behaviors predicated on variable environmental conditions, the child participants became less able to develop abstract explanations for the behavior of the robotic device and were more likely to simply describe the motion of the robotic vehicle. This was true even when kindergartners programmed the complex, conditional behavior of the robot themselves (Levy & Mioduser, 2010). From a Piagetian perspective, difficulty for kindergarten-age children in understanding relationships among more variables than one is not surprising, as students at this age demonstrate centration, the tendency to attend to a single aspect of a problem ignoring other aspects (Piaget & Inhelder, 1969/2000). In this way, the results of these studies are not novel. Moreover, the small number of students in these case studies limits their generalizability to a larger group, so we should interpret the findings with caution. Still, the studies do demonstrate an interesting use of robotics in early childhood teaching, which is to enable student's causal reasoning abilities.

Conditional reasoning. Problems with understanding conditional reasoning are also evidenced among middle-school-aged students (Keselman, 2003). Conditional reasoning underlies the logic of programming environmental sensors to work with robotic devices; the interaction of the sensors with the microcomputer is a constitutive aspect of robotics as a system. In their case-study research with 12 middle school students, Slangen, van Keulen, and Gravemeijer (2011) found that the students were capable of conditional reasoning (a sensory–reason–action loop) when programming one sensor, but, they experienced difficulty with conditional reasoning when it came to programming contingencies with two sensors. In these more complex cases, students focused on programming in a step-by-step fashion (a reason–act loop). We also found that it is difficult for middle school students to utilize conditional reasoning when working with robotics (Sullivan & Lin, 2012). In a tracking challenge that involved the use of two sensors, we found that of the 24 middle school students participating in the study, 13 avoided the use of two sensors, preferring to use just one in combination with an estimating strategy. Students who used this approach to solving the tracking challenge developed imprecise solutions. While the results of our 2012 study confirm the Slangen et al. (2011) findings, both studies occurred with a small number of students, and in both cases the students were extraordinary. Slangen et al. selected talkative students to take part in their case study clinical interviews; we conducted our research with students who attended the Center for Talented Youth, a summer camp that selects participants based on high levels of performance on recognized achievement tests. Therefore, our combined results, while promising, are tentative and need to be validated with a larger number of diverse learners.

Understanding multivariate phenomena. The challenging nature of conditional reasoning in the context of multiple sensors may result from difficulty in understanding multivariate phenomena. Kuhn (2007) has demonstrated that while middle childhood aged children are able to understand the need to control variables in scientific experimentation, they are not able to understand and use multivariate data in scientific reasoning. And, as Suomala and Alajaaski (2002) have noted, robotics-learning environments are multivariate in nature. Kuhn, Black, Keselman, and Kaplan (2000) argue that it may be the existence of a nonnormative mental model of causality that interferes with students' ability to reason with multivariate data. Normative mental models of causality attribute outcomes in relation to all relevant factors, whereas nonnormative models emphasize the contribution of a single factor in discussing outcomes (Kuhn et al., 2000). Nonnormative mental models of causality are characteristic of middle-school-aged children, and may also be prevalent in adults (Kuhn, 2007). Keselman (2003) has found that explicit instruction and prolonged practice with scientific reasoning with multivariate data can improve children's ability to develop normative models of causality.

Systems understanding. Despite difficulties with multivariate, conditional reasoning, as noted earlier, there is evidence to support the idea that certain middle-school-aged children are able to improve their systems understanding through robotics study (Slangen et al., 2011; Sullivan, 2008). In our work, we found that students significantly improved their systems understanding (as measured by a pre–post test) through participation in a 105-hour, 3-week intensive robotics course. This systems understanding includes the interacting functions of the related parts of the robotics device (microcomputer, actuators, sensors). Furthermore, the development of systems understanding is supported by the activities just discussed (learning to sequence a program, engaging in causal reasoning with dual representations about perceived discrepancies in expected movement, and engaging in conditional reasoning with environmental sensors). The system understanding enabled by robotics forms the upper anchor, or desired endpoint, of the computational thinking learning progression.

From a learning progressions viewpoint, the research into computational thinking and robotics suggests that younger children are capable of sequencing and making causal inferences about simple programs using two representations, whereas older children of upper elementary and middle school age are capable of causal reasoning related to complex programs using two representations and conditional reasoning using one sensor. The development of causal and conditional reasoning is supported through problem-solving activities in a robotics environment. These are promising results of robotics study; however, as noted, each of these studies is limited in terms of the participants (small numbers and selective samples) and the methods (case study). Thus, these findings should be interpreted cautiously; future research that addresses the limitations of these studies is warranted.

Problem solving. Once students have constructed and programmed a robotic device, they begin a troubleshooting cycle of problem solving (Sullivan, 2011), which may constitute the majority of their activity with robotics study. Indeed, high school students who studied robotics in a summer school setting reported that they learned much more about problem solving than they had anticipated at the beginning of the camp session (Nourbakhsh et al., 2005). Due to this significant role, several studies are devoted to investigating how students approach problem solving in robotics.

The results of these studies indicate that most students begin their problem solving efforts in robotics contexts using a trial-and-error method (Barak & Zadok, 2009; Gaudiello & Zibetti, 2013; Lindh & Holgersson, 2007; Sullivan & Lin, 2012; Williams, Ma, Prejean, Ford, & Lai, 2008). The trial-and-error method leads to more errors in programming (Gaudiello & Zibetti) and to conceptually weaker programming solutions (Sullivan & Lin). Over time, students move beyond the trial-and-error method and begin to develop more sophisticated approaches to problem solving. These more sophisticated approaches to problem solving support the development of student reasoning.

In their design-based research study with successive groups of students over a 3-year period, Barak and Zadok (2009) identified two problem-solving approaches used by students. They call these two approaches heuristic searches; in these approaches students leverage the knowledge they have built about the problem, to help them solve the problem. The first type of heuristic search, called the proximity method, involves forward and backward reasoning toward the goal of gradually arriving at a solution. The second approach involves planning, modeling, and reasoning through analogy or abstraction. We have also identified student use of a modeling strategy to reason about robotics problems (Sullivan & Lin, 2012). As noted earlier, in our study, students used either the robotics materials or their own bodies to simulate the desired movement of the robot. In this way, our findings support Papert's (1991, 1993) theory of constructionism; the students reasoned about how the robot should function, prior to programming it, through embodying the proposed movement of the robot. This particular type of embodied cognition is a unique affordance of computational manipulatives. We also identified context-specific strategies that students used to solve the robotics problem that were strong strategies not only for developing solutions, but for developing solutions that evidenced greater conceptual understanding (Sullivan & Lin). The context-specific strategies identified included the use of the various tools available in the robotics system, such as the context sensitive help utility, taking readings with the sensors, and making structural adjustments with the LEGO pieces.

The overlap in our findings with those of Gaudiello and Zibetti (2013) as well as Barak and Zadok (2009) points to a continuum of problem-solving practices ranging from trial and error to more sophisticated modeling approaches. However, as with the other studies covered in this review, there are methodological issues that limit the interpretation of the findings. The small number of students in their study (21) and the fact that the students self-selected into the study as members of a First LEGO League team limit the generalizability of Gaudiello and Zibetti's work. In this way, the students are extraordinary and not necessarily representative of a general populace. Barak and Zadok worked with a large number of students, but there results are derived from field notes, which are subject to the bias of the note taker. The limitations of our study were previously noted.

While the more sophisticated problem-solving approaches appear to be related to reasoning abilities, Slangen et al. (2011) argue that the simpler, trial-and-error strategies are important precursors to conditional reasoning. Moreover, Gaudiello and Zibetti (2013) purport that trial-and-error strategies, in combination with declarative, knowledge-driven strategies, constitute a type of metacognitive strategy that help students define the limits of the problem, an important step in problem solving and engineering design (NGSS, 2013). In this way, it is also possible to consider a continuum for problem-solving activity from trial and error to more sophisticated strategies. Importantly, all of this problem-solving and learning activity supports specific learning outcomes related to conceptual understanding of computer programming.

Learning computer programming with robotics. Several research studies have a strong focus on student learning of computer programming as an aspect of robotics study (Barker & Ansorge, 2007; Nugent, Barker, Grandgenett, & Adamchuk, 2010; Slangen et al., 2011; Sullivan, 2008; Sullivan & Lin, 2012; Wagner, 1999). This research has focused on students' understanding of explicit aspects of the programming environments such as Robolab and Mindstorms, which work with the LEGO robotics systems (Rogers & Portsmore, 2004), including the meaning of specific icons and other symbols (Barker & Ansorge, 2007). Researchers have also focused on student learning of more general computer programming concepts such as input/process/output, iteration, conditional statements, and control structures (Nugent et al., 2010; Slangen et al., 2011; Sullivan & Lin, 2012). For example, in our research we developed a rubric to score student use of less and more sophisticated approaches to creating a programming solution to a light-sensor challenge. Eleven of 24 students developed a sophisticated understanding of control structures in choosing to write a program that executed parallel lines of code simultaneously, while the remaining 13 developed a good understanding of using environmental feedback to trigger events on the device. Also, Slangen et al. found that students progress in their understanding of how to sequence the robotic program, starting with a simple reason–act sequence and moving to more complex sense–reason–act sequences. Overall, research indicates that students significantly improve their understanding of the programming environment through curricular intervention with robotics. While these results are promising, they should be interpreted cautiously, as each of the studies has limitations related to their generalizability (see Table A1 for descriptions of specific limitations).

Having just presented our synthesis of the research on RCKs as first-order computational manipulatives focusing on three interrelated facets, (a) computational thinking, (b) problem solving, and (c) computer programming, we now focus on the research related to second-order uses of RCKs.

Second-Order Uses of RCKs as Computational Manipulatives

As defined earlier, second-order uses of robotics as computational manipulatives align conceptually with the traditional notion of educational manipulatives; the robotics system is used as an analogical representation that serves to bridge understanding of concepts in the target domain. In order to accomplish this, the robotics system is used to model systems and concepts from the target domain. For example, Cuperman and Verner (2013) have students use robotics materials to model biological systems—such as predatory plants (e.g., the Venus flytrap). However, few research articles have examined second-order uses of RCKs; those that do exist focus on learning in physics and biology at the middle and high school levels and on the development of science literacy at the middle school level. Due to the small number of articles devoted to this topic, meaningful synthesis is not possible. However, we believe that the notion of second-order uses of RCKs as computational manipulatives is an important one. There is much room for further research in this area, and given the emphasis on both engineering and modeling in NGSS (2013), we believe it is important to consider. Hence, in the following paragraphs we address each article's contribution to current knowledge in this area.

As with the articles focusing on first order uses of RCKs, the limitations of these articles are provided in Table A1 and discussed in the following.

Research on physics learning with robotics. Research on the use of robotics to teach physics has primarily focused on Newtonian kinematics, and, in particular, topics related to forces and motion. The sparse research results in this area are mixed. For example, in a study with fourth, fifth, and sixth graders ($N = 453$) that focused on programming, problem solving, and physics, Wagner (1999) compared students' understanding of forces and motion concepts as measured by a valid and reliable textbook chapter end test (Shymansky, Romance, & Yore, 1988). Students in this classroom-based study were randomly assigned to a robotics treatment group or a battery-powered manipulative group. Students at two other schools comprised a no-intervention control group. Wagner found no significant difference between groups on the textbook test of physics understanding. She argues that the textbook test may not have been able to adequately measure differences in understanding developed through the use of the robotic device.

However, in more recent research, Mitnik, Nussbaum, and Recabarren (2009) and Mitnik, Recabarren, Nussbaum, and Soto (2009) did find a significant improvement in student graph interpretation skills in the area of kinematics through participation in a robotics intervention in a formal 11th-grade physics class and in an informal summer camp program for teens. In both of these studies, students worked on programming, observing and graphing several trials of a robotic vehicles movement. Study results demonstrated significant gains on the Test of Understanding Graphs in Kinematics (TUG-K) used in both projects. The TUG-K is a valid and reliable, 21-question, multiple-choice test designed specifically to measure graph interpretation skills in kinematics (Beichner, 1994). However, these results should be interpreted cautiously, as both studies featured small samples and one study lacked a control group. Because of this, it is not possible to completely isolate the role of the RCKs in the growth of student understanding.

Research on biology learning with robotics. Two research studies focused on the use of robotics to teach concepts in biology. The first study, conducted by Whittier and Robinson (2007), used a robotics curriculum to teach 29 non-English-proficient students (recent immigrants from Mexico) about concepts in evolutionary biology. The textbook curriculum covered the concepts of common ancestry, natural selection, adaptation, evidence of evolution, extinction, and niche specialization. In the study, students were provided a constructed car that they were allowed to modify, including changing the tires and/or the gear ratios. The students designed cars to be either generalist or specialist in relation to four behaviors, including climbing, hauling, strength, or speed. They then engaged in competitions related to each behavior with the robotic vehicles. At the end of each competition, the student and teacher discussed "how the various structural changes to the bots could be analogous to the natural world" (p. 23). The researchers conducted pre and post assessment of student learning in this curriculum using the textbook test (Wolfe, Bernstein, Schachter, & Winkler, 1998). While the students continued to struggle with the material, they did demonstrate a 15.4% gain on the textbook test of evolutionary concepts after studying with this curriculum. Whittier and Robinson argue that the hands-on approach of using robotics to teach evolution created a stronger context for discussing the concepts and theory, which they found to be clearly reflected in evaluations of student writing on the topic. These findings, however, should be interpreted cautiously. As noted in Table A1, we found the research report to be lacking in key details related to both the rubric used to score the student's written work and the textbook assessment of evolutionary content knowledge. The trustworthiness of these findings would be improved if this information had been included in the report.

Meanwhile, Cuperman and Verner (2013) conducted an exploratory, comparative case study on student learning in biology with robotics that focused on modeling biological systems. Twelve preservice teachers and 14 high school students took part in the study. The activities in the intervention included selecting a biological system to study (e.g., the trapping of prey in a Venus flytrap plant) and then modeling that system with robotics materials. The preservice teachers indicated that it is important for high school students involved in modeling biological systems to realize that the constructed model will most likely be a simplified version of the real system. This is important in terms of avoiding the development of misconceptions related to the complexity of a given natural system. As regards the high school students, the study results indicate that creating a functioning model of a biological system necessitated close attention to the mechanisms responsible for the functioning in the natural world. The researchers claim that this attention led to specific insight about these mechanisms. However, as noted in Table A1, there are several limitations to this study that attenuate the impact of the results; for example, no baseline biological systems information was gathered on the students, so it is not possible to gauge the change in knowledge after the modeling activity. Moreover, the report suffers from a lack of detail as regards the data analysis and triangulation methods.

Research on developing science literacy through the engineering design process. Research related to robotics and science literacy points to the fact that while involved in robotics study, students are actively engaged with the habits of mind typical of scientifically literate people, including observation, evaluation of solution, estimation, hypothesis generation, hypothesis testing, control of variables, manipulation, and computation (Sullivan, 2008; Williams, Ma, Prejean, Ford, & Lai, 2008). As can be seen from the prior discussion of NGSS (2013), these habits of mind are an integral part of the engineering design process and they are the constituent activities of engaging in challenge-based robotics study. The troubleshooting cycle facilitated by discrepancies between the expected and actual observed movement of the robotic device include diagnosis (observation, evaluation of solution, hypothesis generation), revision (manipulation, computation, estimation, control of variables), and retest (hypothesis testing, observation, evaluation of solution, hypothesis generation) (Sullivan, 2008). This cycle may recur many times before an acceptable solution to the robotics challenge is found. The engineering design cycle parallels the scientific method; both contribute to the evidence-based thinking skills needed for science literacy (with the appropriate experiences and scaffolding). However, Williams, Ma, Prejean, Ford, and Lai (2008) argue that significant, longer term experiences are needed for science inquiry skills to fully develop. Moreover, research from the broader category of design-based science indicates that multiple varieties of teacher and peer scaffolding are required to fully realize the affordances of design-based science, of which robotics challenges are a subset (Puntambekar & Kolodner, 2005).

Discussion

Key Findings

In this article, we have presented a discussion of RCKs as computational manipulatives for P–12 learning in the STEM disciplines for typically developing children. Our research synthesis has resulted in the development of four key insights that are new to the field as follows: (a) the identification of first- and second-order uses of RCKs—a form of double application that is unique to RCKs; (b) the additional routes to learning made possible by specific features of RCKs, including immediate feedback and dual modes of representation; (c) the formulation of a computational thinking learning progression associated with robotics study; and (d) the conceptualization of a problem-solving continuum from trial-and-error to heuristic approaches made possible through robotics study.

As regards double application, RCKs and other computational manipulatives constitute a special case of manipulatives in that one may use them for both direct and analogic representation, dependent upon the domain of interest. We have characterized direct representation as a first-order use of robotics and analogical representation as a second-order use of robotics. Only computational manipulatives have such a double application (direct or analogical). Moreover, our synthesis emphasizes how RCKs provide additional routes to learning through the provision of immediate feedback and dual modes of representation (two-dimensional [2D] screen representation of a program and three-dimensonal [3D] execution of a program), which stimulates specific cognitive activities, including reflection, discussion, comparative analysis, interpretation of discrepant events, causal inference, causal reasoning, and iterative problem-solving cycles. Only RCKs provide such immediate feedback and dual modes of representation.

Though each of the papers reviewed here is limited in terms of participants and methods, from this corpus we can begin to glean the potential of robotics for supporting student STEM learning in P–12 settings. We have identified a possible computational thinking learning progression with robotics that begins with a lower anchor of supporting students' sequencing ability, moves through a progressive reasoning trajectory from causal to conditional, and arrives at an upper anchor of improved systems understanding. Each of these elements, the ability to sequence, the ability to engage in causal and conditional reasoning, and the ability to understand and engage with systems in a meaningful way, is important for learning across the STEM disciplines, as they are all aspects of computational thinking (Wing, 2006).

In addition to this potential learning progression, these studies all provide evidentiary support for the notion that students learn computer programming concepts and engineering content while studying with RCKs. Furthermore, the research supports the assertion that problem solving is improved for students engaged in a robotics curriculum. For example, students may move from basic forms of problem solving, such as trial and error, to more sophisticated modeling approaches. Problem solving is also an aspect of computational thinking. We have treated it separately in this review due to the large number of robotics studies that directly addressed problem solving.

As noted earlier, only a few studies have, thus far, been devoted to the use of RCKs as second-order computational manipulatives; this research focuses on learning in the domains of physics and biology and in the development of science literacy. While limited, this initial research appears to indicate that the programmable nature of robotic vehicles may be meaningfully employed to help develop students' science literacy and to demonstrate concepts in a forces and motion curriculum. Meanwhile, the mechanistic nature of robotics systems (cognition, perception, and locomotion) may be useful in modeling functional behavior in a biological system. Robotics construction kits as computational manipulatives appear to provide rich opportunities for learning in the STEM disciplines from either a first-order (direct learning) or second-order (analogical/modeling) application.

Limitations

The somewhat small number of qualifying studies is an obvious limitation of this review and of our key findings. In addition, each of the studies reported here has limitations in terms of the number of participants, the number of observations, and the duration of the intervention. Interventions of a short duration have less of an impact on student learning than a longer intervention (Nugent et al., 2010). Moreover, some of the studies have other issues, including bias introduced through the use of various methods, such as self-report instruments, and in some instances, there is a lack of detail related to data analysis, assessment, and triangulation. These issues limit the interpretation of the results.

Furthermore, the proposed learning progression mainly focuses on reasoning. It is possible that reasoning is but one element of a larger underlying set of interrelated constructs (these might include engineering practices, and programming and building skills) that may be part of a robotics learning progression. More research is needed to define the scope of the learning progression. Given these limitations, we view these findings as preliminary. Yet a goal of qualitative educational research is to map out, descriptively, the learning terrain. These studies, taken together, help us begin to build a picture of what is possible with robotics, as well as where we, as educational researchers, may wish to go next in our investigations of these robust technologies for learning.

Implications for Practice

RCKs may be used for many purposes and for children of all ages, from pre-K students through high school. This research synthesis has many implications for teachers in terms of student goals, activity design, classroom environment, and curriculum sequencing. Teachers first need to decide whether they are using RCKs as first-order or second-order manipulatives or both. In other words, does the robotics activity primarily support the learning of robotics and related engineering and programming, or is the activity primarily a means to teach science (or mathematics) content?

For first-order uses, are there specific cognitive skills the activity supports that are age appropriate? It is clear that with certain forms of manipulative robotic environments, young children can meaningfully engage with aspects of computational thinking, most notably sequencing. Also, older children can improve their engineering and computer programming content knowledge while improving their causal and conditional reasoning skills. Moreover, older children can develop improved systems understanding, which may prove helpful in learning about other systems in science. In the case of second-order use, teachers need to scaffold the science learning. Without such scaffolding, students may not effectively use science knowledge in their design activity (Puntambekar & Kolodner, 2005). For both first- and second-order users of robotics, teachers should be aware of developmental considerations in causal reasoning and provide students with experiences that move them in their development of causal reasoning and its related skills: cause and effect, control of variables, multivariate reasoning, conditional reasoning, prediction, and inference.

Another consideration is the design and implementation of the activity itself. As we have seen in this review, RCKs provide a rich environment for the development of many cognitive and content skills. Teachers may wish to focus on specific skills for each project. In terms of implementation, teachers must allow students room to experience failure as part of the engineering process but provide scaffolding as needed to prevent excessive frustration. This type of teaching can be an adjustment for teachers used to providing constant help and answers to students.

Teachers need to examine whether their classroom environment supports the reflection, discussion, and iterative problem-solving cycles required with the use of RCKs. The classroom should also support the NGSS engineering practices most relevant to robotics: defining problems, planning and carrying out investigations, using mathematical and computation thinking, and designing solutions. In the long-term, student practices are just as important as the content learned.

There are also considerations in the development of a program that spans multiple years and follows the proposed learning progression outlined in this article. While the research reviewed looked primarily at short-term experiences, the second author, an elementary technology teacher, has designed a carefully sequenced series of robotics projects that spans pre-K to Grade 6 (Heffernan, 2013). Open-ended engineering challenges are preceded by more well-defined problems that provide the prerequisite building and programming skills needed. In summary, robotics teachers should (a) be clear on their goals, (b) make sure their activity design, implementation, and classroom environment supports those goals and a general atmosphere of design-based learning, and (c) consider how their activity fits as part of a long-term robotics sequence.

Future Research

There is much room for sustained research of on the use of RCKs in teaching and learning. Cross-sectional and longitudinal studies that fully define a developmentally appropriate learning progression with multiple constructs for P–12 robotics would help inform curriculum, instruction, and assessment of P–12 robotics. Additionally, research on conditional reasoning with multivariate data (data from multiple sensors) may be particularly generative and fruitful: The constructionist learning affordances of computational manipulatives, such as immediate feedback and dual modes of representation, may provide stronger cognitive support for the development of such understanding in comparison to other approaches. Learning about multivariate data by programming with multiple sensors may also serve as a rich context for the development of causal reasoning. Future studies in this area should focus on whether and how explicit instruction and/or prolonged experience with programming two sensors, for example, will lead to greater abilities with conditional reasoning and reasoning with multivariate data.

We also need more qualitative research on the analogical uses of RCKs in the sciences, including physics and biology. Future research in this area should utilize assessments that are able to detect learning gains specific to the hands-on nature of the activity. Moreover, additional research could help delineate specific, RCK model-building learning issues, such as the potential for oversimplification of a system, which may be inherent to this method. Finally, qualitative research related to the development of science literacy while using RCKs is also warranted. Such research may focus on the degree to which students are able to actively engage with issues of variability and hypothesis generation, as such, while working with RCKs. This approach would help us develop robotics curricula specifically aimed at the development of science literacy.

RCKs are a powerful technology for learning. Given the engineering focus of the new Next Generation Science Standards (2013), it is likely that the field will begin to see much more research on the use of robotics in P–12 science education classrooms. This article provides a starting point for those interested in conducting research on robotics as computational manipulatives.

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Appendix

Table A1. Summary of Literature Review Results

Author (Year)	Age or Grade	*N*	Research Design (Focus)	Research Goal and Key Findings	Limitations
Barak and Zadok (2009)	Junior high	272	Qualitative—longitudinal case study, observation and interview (problem solving)	How do students come up with inventive solutions, what knowledge do they address, and how do they regard and use information in a problem based robotics context? Students intuitively used heuristic search to find solutions to problems, but could not articulate their strategies. Students developed qualitative systems knowledge to solve problems through tinkering, which later became planning. The authors suggested that it is useful to explicitly teach pupils basic procedural knowledge on scientific, technological, problem-solving, and design concepts.	Case study is more appropriate for small numbers of participants. Therefore, the data collected in this study, in terms of both field notes and interviews, are biased by the subjectivity and focus of the note taker. It is not possible to follow the actions of 80 people at a time. Therefore, the note taker had to selectively focus attention, biasing what was observed.
Barker and Ansorge (2007)	9–11	32	Quantitative—quasi-experimental, two-group, comparison (STEM learning)	To determine the effects of the 4H robotics curriculum on student achievement in science, engineering, and technology. The experimental group did significantly better on the posttest than did the control group. The effect size was large, $r = .943$.	Small number of participants in the study. The achievement test used in this study focused on participants' understanding of the Robolab software. Participants in the control group would have no chance of knowing this information. Hence, the comparison is suspect. Results are not generalizable beyond participants.
Bers (2007)	6–7 and their parents (no ages provided for adults).	80	Qualitative—case study (video observation, interviews, artifact analysis) and questionnaire.	There are three purposes of project interactions. One was to look at the learning environment/approach (constructionist pedagogy) in a family community of practice, the learners (who participates), and the learning outcomes. Key findings—children were able to engage with the "big ideas" of engineering in a robotics context, including engaging in engineering design, programming, and mechanical building.	Self-report was used as a measure of student learning for both the children and the adults in this study. Self-report has a number of limitations, including social desirability bias in which the respondents reply in such a way as to please the researchers. Also, this is a large number of participants for a case study.

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Table A1. (Continued)

Author (Year)	Age or Grade	*N*	Research Design (Focus)	Research Goal and Key Findings	Limitations
Cuperman and Verner (2013)	Middle/high school students, pre-service teachers	146	Qualitative—multiple case study (four cases) and questionnaires.	The purpose of this study was to examine the learning efficacy of an integrative model for exploring a biological system through development of a robotic model of that system. Key findings are that through the process of robotic construction students were compelled to continually reflect upon the essential elements of the biological system they were modeling and to concern themselves with an evaluation of whether and how their model reflected the system accurately. The students were able to develop good models of the biological domains through this method.	The limitations of this study regard the lack of a content-based measure for clearly understanding the change in student knowledge from pre to post modeling. Such a measure would provide a much stronger indication of the learning efficacy of this approach. Also, the samples were ones of convenience, so it is not clear whether and how selection characteristics interact with the key findings. Other limitations include a lack of detail in the data analysis methods used, as well as a lack of detail in how data triangulation was achieved.
Gaudiello and Zibetti (2013)	6–10	26	Qualitative—case study observation (problem solving, heuristics)	This study focuses on the kinds of control heuristics (strategies) students employ in solving robotics problems, from a cognitive psychology perspective. Will students move through a progression of heuristic approaches from procedural (trial and error), to declarative (reasoning) to metacognitive (trial and error + reasoning)? Students used each type of heuristic: procedural, declarative, and metacognitive, but they were more likely to move from a procedural approach to a metacognitive approach, than from a procedural to declarative or a declarative to metacognitive approach.	Small number of participants in the study. Selectivity of participants (self-selected into First LEGO League). Small number of observations (participants worked in groups of three or four, completed two tasks over a 30-minute period).
Kazakoff and Bers (2012)	K	54	Quantitative—quasi-experimental, 2 × 2 × 2 analysis of variance (ANOVA; private vs. public school students, tangible K curriculum vs. art curriculum, tangible K vs. regular curriculum) (Sequencing)	What is the impact of robotics programming on sequencing ability for kindergarten students? Results showed increases in sequencing abilities especially when students worked with a teacher who had experience with the technology.	Relatively small number of participants in an experimental study. Used pictorial cards to test participants' ability to sequence a story. There is no description of the cards and/or whether or not the story sequences would be familiar to participants. No effect size reported. Not generalizable due to small number of participants.
Kazakoff, Sullivan, and Bers (2013)	K	40	Quantitative—repeated measures, paired-	What is the impact of an intensive one-week robotics program on kindergarten children's ability to sequence elements in a story? Study showed significant increases in sequencing in a storytelling	Lack of information on the length of the intervention. No effect size reported.

			sample *t*-test (sequencing)	context for students using LEGO WeDo robotics and the researcher's own Creative Hybrid Environment for Robotic Programming (CHERP) system.	
Levy and Mioduser (2010)	K	6	Qualitative—case study observation (causal reasoning, inference)	To examine the level of understanding of conditional reasoning young children could achieve while engaging with programmed robots. There were two conditional rules and four possible programs students could observe. The programs were progressively more complex. Children were able to explain the movement of the robot in terms of one rule, but not two. However, they could program the robot, using the provided interface, to function at the highest level of complexity. The researchers also identified two strategies students used to interpret existing complexity to a simpler level, pruning and fusing.	Small number of participants in the study. Small number of observations in study (total corpus of student utterances = 341). Report is unclear as to how many of the six participants were able to articulate the movement of the robot in terms of one rule and how many participants engaged in the pruning and fusing strategy.
Lindh and Holgersson (2007)	11/12 and 14/15	696	Quantitative—quasi-experimental, multigroup comparisons (problem solving and math)	Longitudinal quantitative study focusing on whether the use of LEGO improves logical problem-solving skills and mathematics understanding. While results showed no general improvement for the treatment group at large, subgroups did show improvement suggesting that LEGO, as used in the study, could help improve logical problem-solving skills for students who score in a medium range in mathematics in the fourth grade.	No description of the robotics curriculum participants took part in over the academic year. Curricula were taught by different teachers around the country; differences in the effect of the teacher, differences in school culture, and individual differences were not accounted for. No effect size reported. Not generalizable beyond the participants in the study.
Mioduser, Levy, and Talis (2009)	K	6	Qualitative—case study observation (causal reasoning, inference)	This qualitative study examined how kindergarten-aged children interpret robot behavior, how they name rules, scripts, and episodes. As the number of rules increases, the children found it increasingly difficult to specify the rules without adult support and increasingly used anthropomorphic explanations.	Small number of participants in the study. Small number of observations (corpus of utterances = 341). Lack of disambiguation of student achievement without help and student achievement with help.
Mitnik, Nussbaum, and Recabarren (2009)	16	24	Mixed-methods—qualitative case study (video observation, field notes) and quasi-experimental repeated measures	The purpose is to investigate student cognitive processes (collaboration and mediation) while studying Newtonian kinematics and plotting on a graph (graphing distance over time) with the help of personal digital assistants (PDAs) and robotic devices. The key findings indicate that students' understanding of graphing (as measured by the	The limitations of this study include the lack of a control group for the TUG-K assessment, and a convenience sample of participants. Also the report lacks discussion of a systematic approach to analyzing the qualitative data collected in the study. This attenuates the strength of the qualitative

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Table A1. (Continued)

Author (Year)	Age or Grade	*N*	Research Design (Focus)	Research Goal and Key Findings	Limitations
			(pre–post test of understanding graphs in kinematics, TUG-K).	TUG-K instrument) significantly improved through this learning activity.	interpretation of why the students learned in this activity.
Mitnik, Recabarren, Nussbaum, and Soto (2009)	16	23	Mixed methods—qualitative (video observations, self report surveys). Quasi-experimental—two groups (experimental and control) repeated measures (pre–post test of understanding graphs in kinematics, TUG-K).	The purpose was to investigate how a collaborative, hand-held graphing tool (graph plotter) supported student learning of physics (as instantiated by the robotic device) and graphing in comparison to students who used a noncollaborative simulation graph plotter program on a computer. The key findings are that, while all of the students in the study improved their understanding of graphing from pre to post, the group that worked collaboratively with the hand-held graph plotter achieved a much greater effect size in the amount of their improvement from pre to post. This difference is attributed to the level of collaboration required among those in the experimental group.	Limitations include a lack of detail in the formation of the control and experimental groups. For example, there is no indication as to whether the students were randomly assigned to one or the other group. Also, the group being studied was attending a private summer school program, which may have a selection bias as regards participants. Because of this, it is not possible to generalize the results. Also, there is a lack of discussion of systematic analysis of the qualitative data. Hence, findings related to such are less than trustworthy.
Nourbakhsh et al. (2005)	High school	28	Qualitative—case study observation, interview and survey (STEM learning and self-efficacy)	Study focused on the educational impact of a mobile robotics course on secondary students. Student self-report evaluations showed positive results for robotics, programming, teamwork, and problem solving. Girls struggled more with programming; they have less initial self-confidence. However, girls reported that their self-confidence increased as a result of the experience.	Self-report methods fail to control for a number of biases that originate from the subject her/himself. No systematic analysis of the observational data collected in the study. Data not used to triangulate self-report findings.
Nugent, Barker, Grandgenett, and Adamchuk (2010)	Middle school	147	Quantitative—quasi-experimental, two-group comparison (STEM learning and interest)	Study focused on how a robotics and geographic information system (GIS)/global positioning system (GPS) curriculum would impact students' learning of and attitudes toward STEM topics. Researchers compared student achievement on a content test of a short-term group and a long-term group. The long-term group (one week summer camp) achieved greater understanding in math, computer science, engineering, and geospatial skills in comparison to the short-term group, which received a 3-hour	Lack of theoretical basis for teaching robotics and geospatial curricula together. Lack of theoretical basis for why these topics would lead to improvement in engineering and mathematics abilities.

				lesson. However, the short-term group did show increases in STEM interest/attitudes.	
Slangen, van Keulen, and Gravemeijer (2011)	10–12	12	Qualitative—case study observation and clinical interview (robotics understanding)	What do students understand about robots and how do their concepts develop? The researchers define taxonomy of cognitive levels related to robotics understanding: psychological, technological, and functional, as a controlled system. Students move up the levels with teacher support. They also define an S-R-A loop: sense, reason, act, which they feel is important for robotics understanding.	Small number of participants in the study. Selectivity of participants (talkative). Relatively small number of observations of participants (six dyads followed for 2 hours, three of these dyads followed for subsequent five sessions of 2 hours each).
Sullivan (2008)	11–12	26	Mixed methods—observational, repeated measures (systems understanding, science process, thinking)	How does engagement with a robotics curriculum provide affordances for the development of thinking skills, science process skills, and systems understanding? Through open-ended exploration and a challenge-based robotics curriculum, students improved their content knowledge, thinking skills, science process skills, and systems understanding.	No control group for systems understanding test. Small number of participants in study. Small number of observations—1-hour problem solving challenge, undertaken in the context of a 135-hour course on robotics. Participants were students attending a selective summer camp designed for high achieving students. Results are not generalizable beyond the participants in the study.
Sullivan (2011)	Grade 6	4	Qualitative—microgenetic case study observation (collaborative creativity)	To understand how a creative solution to a robotics challenge emerged in a collaborative group from a dialogic perspective. Four contextual aspects allowed the creative, collaborative solution to emerge: open-ended, goal-oriented task; teacher modeling of inquiry; environment and tools that allowed for both seriousness and play, and tools and environment that allowed a shared understanding achieved through tool-mediated, communicative, and cognitive interaction.	Small number of participants in the study (3). Interpretation of data is not triangulated through second source of data, such as interviews.
Sullivan and Lin (2012)	11–12	22	Mixed methods—observational/ correlational (sociocognitive factors and problem-solving approach)	What is the relationship of middle school students' perceptions of the ideal science student to their problem-solving activity and conceptual understanding in the applied science area of robotics? Students with a process-oriented view of science were more likely to use specific problem-solving strategies and showed stronger conceptual understanding than students with a personal traits-oriented view of the ideal science student. The latter evidenced the use of general problem-solving	Small number of participants. Small number of observations—1-hour problem solving challenge, undertaken in the context of a 135-hour course on robotics. Participants were students attending a selective summer camp designed for high-achieving students. Study is not generalizable beyond participants.

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Table A1. (Continued)

Author (Year)	Age or Grade	*N*	Research Design (Focus)	Research Goal and Key Findings	Limitations
				strategies and developed conceptually weaker programs.	
Wagner (1999)	Grades 4, 5, 6	453	Quantitative—experimental factorial design analysis of covariance (ANCOVA); programming, science literacy (inquiry skills), and problem solving.	Author hypothesizes that studying physics with a computational manipulative may result in significant gains in both problem solving and physics content understanding. Study compared robotics, battery-based manipulative, and traditional learning approaches. This early study found gains in programming and problem solving for robotics-based approach but not for physics content learning.	The small effect size (Cohen's $d = .2$) in relation to the problem-solving assessment limits the generalizability of the results.
Whittier and Robinson (2007)	Grades 7–8	29	Mixed methods—qualitative case study (observation, field notes, artifact analysis). Pre–post assessment of knowledge of concepts and theory of evolution. Pre–post assessment of English writing skills.	The purpose of this study was to investigate the efficacy of using robotics to teach about evolution, especially in the context of students with limited English language proficiency (in this case, recent immigrants from Mexico). Key findings indicate that students' understanding of the evolution concepts and their English writing skills improved over the course of the 12-day curriculum. Writing score went from 2.1 to 3.0 and their evolution knowledge improved from 26.9% to 42.3% on the test.	Limitations of this study include a lack of theoretical grounding for why the RCKs might help students learn evolution. Also, the lack of a control group attenuates the strength of the findings as related to robotics. Students might have learned as much if taught evolution using a different method. Furthermore, there is a lack of detail related to both the writing assessment and the content test of evolution.
Williams, Ma, Prejean, Ford, and Lai (2008)	Middle school students and adult facilitators	31	Mixed methods—repeated measures, field notes, facilitator focus group and individual interviews (science literacy–inquiry skills)	This study investigated the effect of a 2-week robotics summer camp on middle school students' physics content knowledge and scientific inquiry skills. Results of the study indicate science content gains but not science inquiry skill gains. Researchers recommended that students explicitly describe science concepts and inquiry that occurs and that curriculum and teacher training support science inquiry skills explicitly.	Small number of participants in study (21 students, 10 adult facilitators). No control group for achievement measures ($n = 21$). No effect size reported. Lack of reporting on the reliability and validity of the instrument. Study is not generalizable beyond the participants.