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Making Sense by Building Sense: Kindergarten Children's Construction and Understanding of Adaptive Robot Behaviors

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Abstract This study explores young children's ability to construct and explain adaptive behaviors of a behaving artifact, an autonomous mobile robot with sensors. A central component of the behavior construction environment is the RoboGan software that supports children's construction of spatiotemporal events with an a-temporal rule structure. Six kindergarten children participated in the study, three girls and three boys. Activities and interviews were conducted individually along five sessions that included increasingly complex construction tasks. It was found that all of the children succeeded in constructing most such behaviors, debugging their constructions in a relatively small number of cycles. An adult's assistance in noticing relevant features of the problem was necessary for the more complex tasks that involved four complementary rules. The spatial scaffolding afforded by the RoboGan interface was well used by the children, as they consistently used partial backtracking strategies to improve their constructions, and employed modular construction strategies in the more complex tasks. The children's explanations following their construction usually capped at one rule, or two condition-action couples, one rule short of their final constructions. With respect to tasks that involved describing a demonstrated robot's behavior, in describing their constructions, explanations tended to be more rule-based, complex and mechanistic. These results are discussed with respect to the importance of making such physical/computational environments available to young children, and support of young children's learning about such intelligent systems and reasoning in developmentally-advanced forms.

Keywords Robotics concepts · Cybernetics · Preschool education · Behavior construction · Adaptation · Emergence

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1 Introduction

This paper is one of two (Levy and Mioduser 2010) in which we report on young children's ability to plan, implement and explain the adaptive behavior of a behaving artifact—a Lego-made robot with sensors. As we will show, young kindergarten children are capable of conceptualizing the robot's behavior in terms of abstract rules (making sense) and using such rules to construct the robot's behaviors (building sense).

A central component of the research setting is the RoboGan environment developed for this project (Mioduser et al. 2009). This environment structures the children's interactions with a physical robot's "mind" and includes a progression of interfaces adapted to their growing understanding. We portray this environment and how the children utilize its affordances when constructing sophisticated robot behaviors. We explore their constructions and explanations of these constructions for increasingly complex behaviors.

The main thrust of our argument as to the importance of activities and learning involving young children's construction of adaptive robot behaviors is based on three claims. One claim is the pervasive presence of artificial autonomous decision-making systems in our everyday environment. The second claim is the potential for children's intellectual development, specifically causal and rule-based thinking about emergent processes. Third, is the constructionist claim promulgating creative construction and engagement in playful and social interaction with such systems (Papert 1980/1993). This argument -and underlying claims- are developed in the next sections.

Artifacts capable of adaptive behaviors are part of our everyday environment at home, school, in- and outdoor environments, and work and leisure places. Young children encounter these artifacts as sophisticated toys, computer-controlled games and devices, kitchen appliances, elevators and automatic doors, traffic light systems, and many other controlled systems. This new "breed" of human-mind-made artifacts that began populating our world only a few decades ago is capable of purposeful functioning capabilities, autonomous decision-making, programmability, knowledge accumulation capabilities, and adaptive behavior—challenging children's traditional and intuitive distinctions between the living and non-living (Gelman and Opfer 2004).

In previous papers we have reported on our examination of children's *perceptions* and *explanatory frameworks* concerning demonstrated artificial adaptive behaviors of simple robots (Levy and Mioduser 2008; Mioduser et al. 2009). Children's explanations of the robots' functioning in diverse scenarios and situations were analyzed, unveiling various layers in their conception of the nature and causes of adaptive behavior in artifacts. In this paper we intend to go deeper into children's conceptions changing the focus of our analyses from their explanations of *demonstrated* adaptive behaviors, to their performance while engaged in *constructing* a robot's adaptive behavior. In another study that analyzes the same dataset (Levy and Mioduser 2010), we provide detailed evidence regarding the process of learning by which children transition in their understanding of the system, adapting to its language and necessary spatial coordination, relating rules and ongoing behaviors and confronting complexity that is greater than they can incorporate into their articulations.

The main question we address is whether and how active involvement in constructing a robot's behavior, in a series of tasks of increasing complexity, affects the children's understandings and conceptions. More specifically, we will report on our findings concerning the following questions:

Question 1 What do children *do* when they construct artificial adaptive behaviors? Are they capable of constructing such behaviors? If so, how close are their initial programs to their final successful ones? What adult support is necessary to help them succeed at the task? What problem-solving strategies do they use in debugging their programs? To what degree do they employ the RoboGan's proclaimed affordances?

Question 2 What do children *say* (explain) about their constructions of artificial adaptive behaviors? What constructs (episode, script, rule) do they use to frame their articulations? How many rules can they integrate in their descriptions? How do they relate the emergent (intentional) behaviors with the underlying (technological) rules in explaining the robot's behavior?

By examining these questions we wish to contribute to current theoretical and research knowledge at three main levels: (a) young children's understanding of artificial adaptive behavior; (b) the potential role of the (demands and affordances) of behavior-construction processes for stretching their developmental boundaries as reported in the literature (e.g., Metz 1991); and (c) the role of the partners in the working/learning environment (adult, interface, physical system) for supporting these understandings and conceptions.

Children's *doing* and *saying* were examined while solving a progression of tasks of increasing complexity, using the RoboGan computer interface which allows the construction of behavior rules for controlling a robot's functioning. A brief account of the rationale of the study and the construction environment developed for the young children will be presented in the next section (for a more detailed description see: Levy and Mioduser 2008; Mioduser et al. 2009). Specific reference to the tasks, the variables and main themes of the study will be presented in the Method section.

2 Background

In focusing upon children's construction of a robot behaviors, and on their explanations of such constructions, several lines of previous work are of relevance: (a) children's conceptions of a robot's behavior in terms of the complex interactions between the physical components, the control program and features of the environment; (b) children's work with robotic systems, and the rationale (pedagogical, cognitive, developmental considerations) for using such systems in educational settings; (c) conceptual approaches towards the construction of a robot's adaptive behavior; (d) developmental affordances and constraints while engaging with the complexity of the behavior-construction tasks. A comprehensive review of these lines of work is beyond the scope of this paper. In the following we will briefly refer to previous work focusing on young children's conceptions of artifacts' adaptive behavior and their ability to construct artifacts' behaviors.

2.1 Conception of Artificial Adaptive Behavior

The research literature refers to a number of dyads describing people's stance toward artifacts: *animate* or human-like *intention* versus *inanimate* technological *purpose* (Ackermann 1991; Turkle 1984; Scaife and van Duuren 1995; Okita and Schwartz 2006; Bernestein and Crowley 2008; Jipson and Gelman 2007); *function* versus *mechanism* (Piaget and Inhelder 1972; Granott 1991; Metz 1991; Levy and Mioduser 2008); *function* versus *physical appearance* (Kemler Nelson and 11 Swarthmore College Students 1995; Diesendruck et al. 2003) and original (designer's) *intended function* versus *current function* (Bloom 1996; Matan and Carey 2001; Defeyter 2003).

The ambiguous status of computational objects among artifacts was demonstrated in a series of developmental studies (van Duuren and Scaife 1995, 1996). Artifacts with different anthropomorphic features (a remote-controlled robot, a computer, a doll, a book) and a person were used to elicit children's associations as regards to various issues, such as mental acts of dreaming, simple motor acts of walking and talking, sensory acts and feelings, and even the very question as to whether the artifacts have a brain. While children's ideas about the doll, the book and the person did not show any differences with respect to previously described development regarding such distinctions, the "clever artifacts" -the robot and the computer- showed clear differences. By the age of 7 years, children construe such intelligent machines as cognitive objects, combining animate and inanimate characteristics. They attribute them with a brain, but not a heart. Between the ages of 5 and 7 years, children begin forming a differentiated concept of "intelligent artifacts" that think, decide and act, have a brain, and are a special category of cognitively competent artifacts; with robots eliciting earlier understandings of such notions than computers. Bernestein and Crowley (2008) explored young children's attribution of intellectual, psychological and biological capabilities to a similar set of items, and how these relate to prior experience with robots. Contrary to the Scaife and van Duuren studies, they did not find comparable age differences. However, greater experience with robots (e.g., building a robot, visiting a website or museum exhibit concerning robots, having a robot toy) was associated with viewing the robot as an intelligent artifact: associated with intellectual capabilities, yet only partially psychological.

Ackermann (1991), in describing children and adults' understanding of complex controlled systems or self-regulating devices, proposes two perspectives: the psychological and the engineering. The *psychological point-of-view* is commonly taken by cognitive psychologists, laypeople and children. Intelligent artifacts are described as living creatures, attributed with intentions, awareness, personalities and volition. The *engineering point-of-view* is typically used when building and programming the system. No intentions are ascribed to the system; its behavior arises from interactions between its components and those with its surroundings, i.e., how one part of the system may move another part. There is no need to go beyond the material parts. Thus, Ackermann separates between a physical-causal and a psychological-animate perception of behaving artifacts. Integrating the two kinds of explanations—synthesis of the behavioral and the psychological—are the core of a whole explanation. She claims that the ability to animate or give life to objects is a crucial step toward the construction of cybernetic theories, and not a sign of cognitive immaturity. In animating the object, it is viewed as an "agent", able to change its course of behavior by its own volition. With development, people progressively disentangle purpose and causality.

In a previous paper we reported on children's perspectives in explaining the functioning of a demonstrated self-regulated robot, in a progression of tasks of increasing complexity (Levy and Mioduser 2008). We have found that the children employed two modes of explanation (in reference to Ackerman's categories): "engineering" mode focuses on the technological building blocks which make up the robot's operation; "bridging" mode tends to combine and align two explanatory frameworks—technological and psychological. However, this was not consistent across tasks. In the easiest tasks, involving a simple decision-making rule, most of the children employed an engineering mode. When the task became more difficult (e.g., more rules were involved in generating the robot's behavior), most children shifted to a bridging mode. In this paper we refer to the effect of engagement in constructing the robot's behavior, i.e., creating its decision-making procedures, on children's evolving conception and explanations of adaptive behavior in artifacts.

2.2 Young Children and Programming

Computer programming environments have had a long history in early childhood education, either as textual-code-based languages, in the form of "tangible programming" (i.e., manipulation of physical components) or as visual programming (i.e., manipulation of visual components on the screen). Undoubtedly, the epitome of a programming language created specifically for educational purposes is Logo (Papert 1980/1993). Since its development in the early 1970s, it evolved over the years and was expanded with sophisticated features (e.g., user-friendly interfaces, debugging tools and feedback support, multimedia manipulation functions), and became subject of numerous studies worldwide (e.g., Clements 1990; Yelland 1995).

Tangible programming evolved from the early days of Tortis, a programming system allowing children to move physical objects to express programs (Perlman 1974; Morgado et al. 2006) through a variety of tools allowing children to program without resorting to textual code (e.g., Horn et al. 2009; Wyeth and Purchase 2000), to programmable bricks and a wide array of computational toys (e.g., the Lifelong Kindergarten project—Resnick 1998; Schweikardt and Gross 2007).

Robots and other adapting controlled artifacts have also had a long history in early childhood education: from the mechanical and programmable 'floor turtle' which drew pictures on paper (Papert and Solomon 1971; Papert 1980/1993), to a variety of robots that children interact with in different ways (Valiant Rover, Macchiusi 1997; AIBO, Fujita et al. 2000; Furby, Maddocks 2000; PETS, a story-teller robot, Montemayor et al. 2000; Bers and Portsmore 2005).

Another approach involves visual or iconic systems. These were developed since the early 1980s with the aim to allow novices to program bypassing the need to remember names of commands and syntax constraints (e.g., PICT, PLAY, at the University of Washington, Kelleher and Pausch 2005; "ToonTalk", Kahn 2004). Currently the 'Scratch' language (Monroy-Hernandez and Resnick 2008, along the lines of its predecessor 'Logo Blocks', Begel 1996) is being used worldwide by children and teachers, in and out of schooling settings.

Concerning empirical evidence on the learning and cognitive effects of the involvement in programming activities with the above tools, the picture depicted in the research literature over the years has been inconclusive and even controversial (e.g., see, Jonassen 2004). For example, early work focusing on Logo reported contrasting results on the effect of programming for the acquisition of cognitive and meta-cognitive skills (e.g., Pea et al. 1985; Clements 1999), thus leading to contrasting conclusions concerning the fulfillment of expectations (e.g., Cuban 1993; Papert 1987). Relevant to our focus in this paper is the question of whether learning a programming language has deeper significance than the actual learning of commands, syntaxes, programming structures and strategies for writing efficient computer programs—looking towards a wider array of implications in realms such as cognitive and meta-cognitive processes, individual and social knowledge-construction processes, learning cultures.

2.3 Programming vs. Behavior-construction

Following Papert's vision and claim that the integration of technological tools into educational processes should focus on learning and cognitive growth rather than on the tools per se, "programming the robot" is redefined in our studies in terms of behavior-construction (or robot's-mind-construction) processes. Through this perspective, the process of constructing a program for the robot is actually an elaboration on the meaning of behavior, goal-oriented decisions, adaptation to environmental conditions, and above all, how to instantiate all this using a behavior-construction formal language.

Building on previous lines of work on: (a) "manipulatives" for knowledge-construction (e.g., Clements 1999; Zuckerman et al. 2005) and (b) iconic interfaces (e.g., Kahn 2004; Monroy-Hernandez and Resnick 2008), we have developed the RoboGan robotics environment for young children (a description is presented in the Method section). The design of this environment supports young children's construction of a robot's behavior out of components presented in visual/iconic form and stresses several conceptual premises:

- It promotes *elaboration-through-construction* processes, in which the construction of the robot's behavior is approached as an evolving task—the interface facilitates decomposition of the overall behavior into either output components or input–output dyads, which can be defined, modified or replaced during construction and further evaluation cycles.
- In a previous paper we have already elaborated on the cyclical process that takes place in the realm of '*concrete-abstractions*' (Mioduser et al. 2009). Contrary to studies which have shown young children's difficulties in forming abstractions (Klahr et al. 1993; Schauble 1990; Kuhn 1989), and congruent with studies that have demonstrated children's capabilities inferring rules from the outcomes of change in physical devices (Frye et al. 1996; Siegler and Chen 1998; Sobel et al. 2004), we have seen in our studies how children spontaneously abstract rules for the robot's behavior. The robot system serves the child as a concrete environment for the exploration and construction of abstract concepts and schemas. Interplay is generated between this 'abstractions-embedded-concrete-agent', and the cognitive abstractions generated by the child. In the realm of 'concrete-abstractions', recurring cycles intertwining the symbolic and the concrete (the behavior-construction interface and the behaving robot) are exercised by the child while abstracting schemas for generating the robot's behavior.
- *Bugs* in the robot's behavior are actually bugs in the behavior-constructor's thinking—about the target behavior and about the way (scripts, rules, routines, programs) to generate it. Consequently, debugging the robot is first and foremost debugging thinking. Well known in the literature on cognition and computer programming, this claim is highly relevant to the RoboGan interface. All components for generating the observed (however, undesired) behavior are on the interface's screen, exposed to analysis/evaluation/reflection by the child. Each and every symbolic component has its counterpart in a concrete behavioral component—any change in a symbolic component immediately affects concrete action. Closing gaps between an observed and a desired state of the robot actually means 'debugging-in-action'.
- Embedded in the interface is *'spatial scaffolding'* of the construction process. Entering every mode of work invokes an empty spatial template on the screen and a toolbox of resources for constructing the behavior. Spatial features support both decomposition of the problem or target-behavior and composition of the solution.

Summing up, in our studies we explore the idea that a programming environment viewed from the above perspective, is in fact a laboratory for thinking, transcending the mere act of writing instructions for a robot to follow. Central to our examinations are learning and developmental processes, and the way children's conceptions of the artificial evolve and are instantiated in adaptive-behaviors construction processes. Whether our conceptual assumptions and the affordances of the working environment have impact upon children's understandings and construction of the robots' behavior is the main question guiding this study.

3 Method

3.1 Participants

Six children participated in the study, three boys and three girls, selected randomly out of 60 children in an urban public school in the central area of Israel (socioeconomic status defined as mid-high). Their ages spanned from 5 years 6 months to 6 years 3 months, with a mean age of 5 years 9 months and a standard deviation of 3 months. At the time of the study, these children were mainly pre-literate: recognizing some of the letters, but not reading; counting but not adding or subtracting to ten. Due to a technical mishap in collecting part of the data, some sections refer to five rather than six children. The children's parents all signed consent forms approving their child's participation in the study, and attrition rate was zero.

It is important to note that this sample is small, due to the exploratory nature of the study. While we do use quantitative terms to describe part of the results, we place a reservation as to their validity.

3.2 Learning Environment

The learning environment is made up of three parts: the RoboGan computerized interface, a sequence of tasks and the interviewers' interventions.

3.2.1 RoboGan Construction Environment

Based on the conceptual guidelines presented in the background section, the computerized *control environment* was designed to scaffold the children's learning processes. This environment includes a computer interface (Fig. 1), a physical robot (made with the Lego system) and modifiable "landscapes" for the robot's navigation (Fig. 2).

A key component of the environment is an iconic interface for defining the control rules in a simple and intuitive fashion (Mioduser et al. 2009). The left panel shows the inputs to the system, information the sensors can collect and transmit. The right panel presents possible actions the robot can perform. The central section is devoted to the "construction board" in matrix form. The configuration of this middle section changes with advancing tasks: starting with one condition-action couple and ending with that seen in Fig. 3: two complete rules or four condition-action couples. Each square shows an action to be performed when the two conditions (row and column) are met.

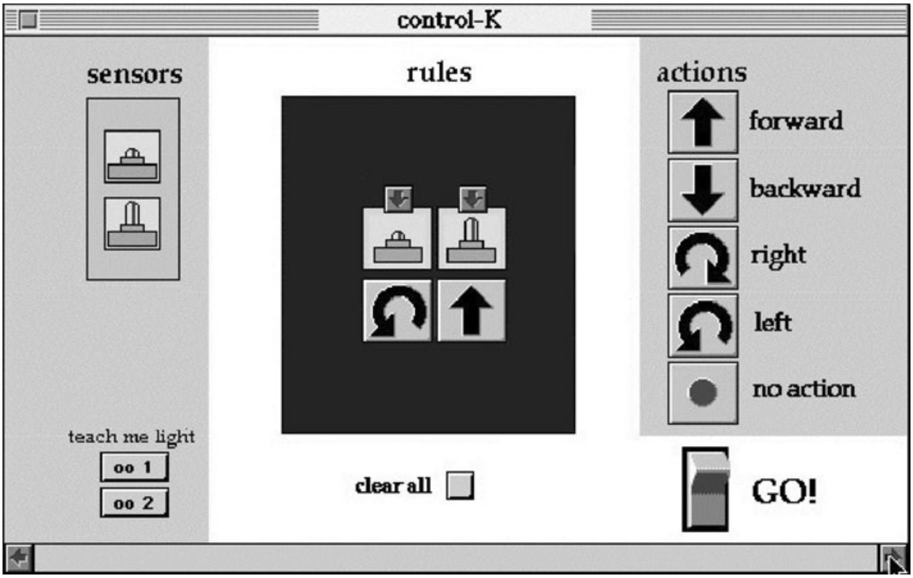

Fig. 1 Screen of the computer control environment for one rule in the "avoid the obstacles" task

Fig. 2 Omer at the computer programming the 'avoid the obstacles' task

3.2.2 Construction Tasks

Construction tasks (see Appendix) were designed as a progression of assignments in which the number of rules used to program the robot increases, as well as the complexity of the robot's overall behavior. Examples of behavior-construction tasks: help the robot move freely in a field with obstacles; have the robot cross a winding bridge without "falling" off. A full description of these tasks is presented in the section delineating the procedure.

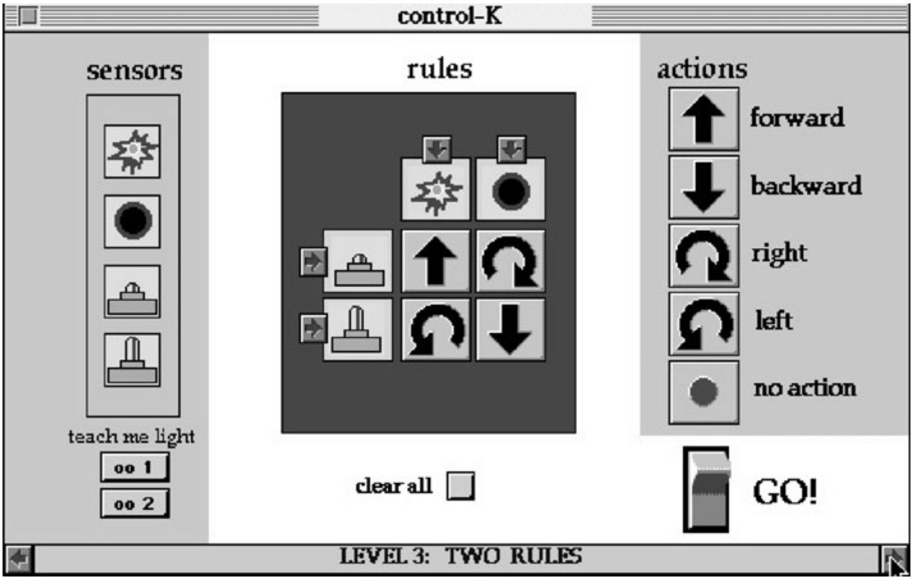

Fig. 3 Sample screen of the computer control environment for two interrelated rules

3.2.3 The Interviewers' Interventions

The interviewers supported the children throughout the sessions in the following ways: introducing the sequence of interfaces and the functionality of their tools and widgets; presenting the task and discussing it with the child until the goal was clarified; following this, support was released—the child is on her own. However, once a hurdle is met and the child does not succeed in overcoming it on her own, "prompting" support was provided to clarify the problem (the child was asked to describe the program or the robot's behavior). When this did not help, "decomposing" support was provided: specific features regarding the environment, the robot's actions or the interface that are relevant to the problem are pointed to, and the child is asked how they impact the robot's behavior. This support targets two goals: increased encoding of the relevant features and decomposing the problem into its components.

Examples of "prompting support" are: [interviewer touches sensor] "*Why do you think that happened?*"; "*Do you want to try something else? What do you want to change?*"; "*What is 'to run away'*?". Examples of "decomposing support" are: "*When he's in that situation, what do we tell it?*"; "*What is the eye seeing now?*"; "*How does it get away from rocks (barriers)?*".

3.3 Procedure

The subjects in our study participated in a sequence braided of two strands of tasks: Description and Construction (Appendix). In this paper we focus on the Construction tasks, in which the child constructs specific robot behaviors (for papers relating to the Description tasks see: Levy and Mioduser 2008; Mioduser et al. 2009).

The tasks make use of the same robot in a variety of physical landscapes, and were designed as a progression of rule-base configurations. The operational definition of *rule-base configuration* is the number of pairs of condition-action couples (If… Then… couples). One *robot control rule* consists of a pair of related condition-action couples (If true … Then…; If false… Then…). The conditions are complementary, i.e., if one condition is “dark”, then the other is “light”. The tasks progress through a range of increasing difficulty: half a rule (one condition-action couple), complete rule (two condition-action couples), two independent rules and two interrelated rules, which are made up of two pairs of condition-action couples.

Figure 4 presents the study design.

Prior to each construction task, the children were presented with a robot operating in an environment, such as circling the perimeter of an island. The child was interviewed regarding this behavior.

A Construction task began with explicating the program controlling the robot’s behavior in the (previously observed) Description task. The child was then presented with a new goal, such as “teach the robot to cross a bridge over water” and proceeded to construct and test this behavior.

An example of a construction task takes place in an obstacle field, through which the robot is required to navigate without getting stuck at the barriers (Fig. 2). The robot has a front-protruding touch sensor that gets pressed when the robot runs into an object. The behavior construction board (Fig. 1) displays the two conditions: having the touch sensor pressed or unpressed. The child pulls the robot’s navigation arrows (forward, backward, turning left and right) into the behavior construction board, aligning them with the appropriate conditions and then presses the Go! Button to run the program. In this example, Omer has constructed the robot’s behavior at the computer, so that upon hitting an object, the sensor gets pressed and the robot turns in one place to the left. When it is free of obstacles, the sensor is not pressed, and the robot moves forward on the board. Putting this all together results in the robot roaming about the field, dodging barriers once hitting upon them and changing direction.

The study lasted five 30–45 min sessions, spaced about 1 week apart. The children worked and were interviewed individually in a small room off the teachers’ lounge. All sessions were videotaped.

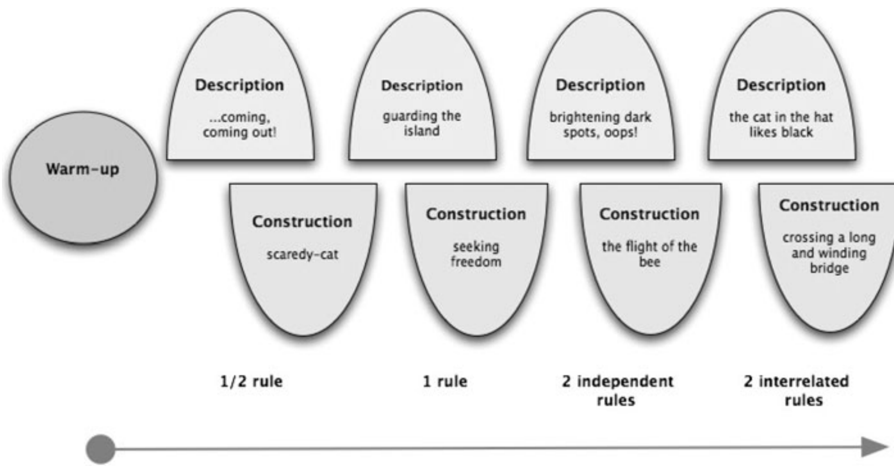

Fig. 4 Study design

3.4 Data Analysis

The main corpus of data consists of (a) the children's behavior constructions in each session; (b) their answers to a question at the end of the session, asking them to describe the robot's behavior. A systematic quantitative analysis is undertaken in this report. We do not describe the data analyses in this section. Rather, they are described in the Findings section in conjunction with reporting on the results.

To establish reliability regarding the coding in the quantitative portions of the analyses, three independent coders (the authors and a graduate student) coded 20% of the transcripts. Inter-judge reliability was 92%. The remaining data were coded by the student and checked by the other judges to uncover obvious errors.

4 Findings and Discussion

The children in our study constructed a robot's "mind". As they engaged with increasingly complex challenges, they constructed the robot's behavior, planned and implemented its underlying rules. Moreover, as we will demonstrate, they interacted with the outcomes of their construction—the robot's actions in physical space. Thus, very often the children take the role, not only of designer and observer, but also that of an *active agent* in the robot's environment, playfully exploring its behavior.

Corresponding with our research questions we separate, and then compare, between what the children *do* and what they *say*. We will first focus on the constructions and their succession (what the children *do*), portraying their success at the behavior construction challenges, the number of debugging cycles and their interaction with the human and computational scaffolds. This will be followed by a presentation and analysis of the children's unaided explanations of what the robot is doing at the end of each construction session (what they *say*)—typifying them in terms of their abstractness, complexity, and their expressed understanding of the robot's behavior as emergent. We focus on these unaided explanations as an indicator of what the children can construct verbally and conceptually on their own, with no support. These descriptions were elicited in a consistent manner while the children's further explanations were varied in adult support and less consistent in the interview protocol. Thus, only the first are analyzed. As we will establish, the children were surprisingly successful in creating the robot behaviors and described their creations with increasing sophistication.

4.1 Research Question 1: What do Children do when they Construct Artificial Adaptive Behaviors?

Findings to question 1 will be presented with regards to the children's success at programming the robot, the number of attempts at programming before they succeeded, and with respect to the two types of scaffolding: adult support and interactions with the RoboGan interface.

4.1.1 Success

The children were *successful* in constructing the robot's designated behaviors in 23 out of 24 sessions. One child did not complete the task in the third session involving two independent rules. The child that did not complete the task constructed the robot's behavior successfully in the following session in two cycles, the shortest solution path among the children. As we will show in the next section, this particular task was distinct from the rest in that the children clustered in two groups: those who succeeded in their constructions within one or two rounds, and those who found the task difficult and needed several rounds of construction to complete the task.

4.1.2 Cycles to Success

As a measure of the tasks' difficulty, the children's constructions are typified by the *number of cycles to success* (see Table 1). A cycle is defined as a program that the child created and tested. Programs that the children made and then changed before trying them out are not counted as a distinct cycle. In addition, programs that were created after completing the task were not counted.

The number of cycles to success is small, ranging from one (no debugging) to six. As the tasks increased in difficulty, the mean number of cycles to success rises from one up to three cycles. The number of cycles is quite small, much smaller than that if the construction were performed randomly. For example, for the one-rule task 16 programs can be defined - of these only two fit the requirements of the task. However, the children succeeded in constructing the robot's behavior in this task in only two to three cycles. This is corroborated in a parallel study of the children's learning processes (Levy and Mioduser 2010). In this research, we have seen that the children's constructions were anticipatory, as they displayed reasonable rules from the start, and in some cases simulated the robot's behavior even before running their programs.

It is interesting to note the larger standard deviation for the third task structured as two independent rules. For this task, the six children split in two groups. One group solved the problem in one sweeping step (two children) or two (one child). The other group solved the problem in the largest number of cycles among all tasks—five or six (two children) and one child did not complete the task. This difficulty is substantiated in the parallel study with the same children, in a vignette that describes Mali's difficulties in articulating the rules for this task. Even when the interviewer prompts her, she can describe only isolated components of the robot's behavior.

Table 1 Number of construction cycles until success

Task	Cycles to success		
	M	SD	Range
Half rule[a]	1.2	0.4	1–2
One rule	2.3	1.0	1–4
Two independent rules[b,c]	3.0	2.3	1–6
Two interrelated rules[d]	3.0	0.6	2–4

[a] One rule is defined as two complementary condition-action couples, such as "if you see light, turn; if you see dark, move forward". Half a rule includes one condition-action couple

[b] Independent rules are defined as rules whose conditions are not logically related, but operate independently of each other (see examples in Appendix)

[c] One child did not succeed in this task and is not included in the statistics

[d] Interrelated rules are defined as rules whose conditions are logically related

4.1.3 Scaffolds

In this study, we explored the children's constructions and understandings as these evolved within a multiple-partners environment, including the child, the adult/interviewer, and the robotic system. The types of interactions between the adult and the child were not of a normal instructional genre: the adult asked questions that supported the children in communicating their ideas, and later probed for their possible extension by asking about unattended environmental conditions or robot actions, thus supporting their encoding of relevant task features (Siegler and Chen 1998). The other partner in the interaction space, the RoboGan robot system, served the child as a concrete tool for the exploration and construction of abstract concepts and schemas. In this section we portray how these scaffolds—human and computational—interacted with the children's activity.

4.1.3.1 Adult Support The role of an adult in supporting the children's learning is portrayed as it interacts with the tasks' complexity. The interviewers supported the children throughout the sessions offering either "prompting" or "decomposing" support (see Method section). The supports are in the form of *questions* and not answers; the children were not "told the answer" but helped to notice features of the problem. From the learning perspective, this protocol serves two goals: increased encoding of the relevant features and decomposing the problem into its components. From the research perspective, the protocol ensured two important aspects in the study: one, that minimum support was provided, maximizing the child's independent activity; second, this form of support serves as a measure for the degree of scaffolding necessary for the child to complete the task.

The adult's support in each of the sessions was coded for the highest-level support between the two levels: if only "prompting" support was provided, it is coded as "light" support; if both "prompting" and "decomposing" support were provided, the session is coded as having "heavy" adult support.

Adult support increased with task difficulty and was mainly "heavy" for the tasks involving two rules or four condition-action couples (Fig. 5). In the task that involved one condition-action pair (half a rule), the children constructed the robot's behavior mainly

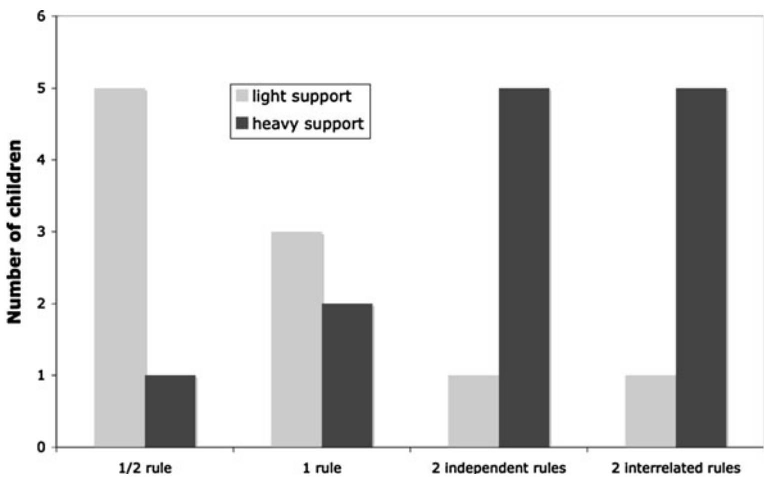

Fig. 5 Adult support of the children's programming

independently. For the two tasks that required the use of two rules, the children's constructions required "heavy" support of an adult. The task involving one complete rule or two complementary condition-action pairs ("if X, then…; if not X, then…") is transitional: some children needed help at this stage; others did not. Similarly, the transitional status of this complexity was observed for the Description tasks (Mioduser et al. 2009) and is well-described in the developmental literature (e.g., Siegler 1986).

4.1.3.2 Interaction with the RoboGan Interface This section documents the children's moves between successive constructions in terms of the RoboGan environment's proclaimed affordances, testing this design. As described in the introduction, the RoboGan's construction board was designed for gradually increasing levels of complexity, and support in focusing the child on the problems' components. Moreover, we claim that the construction board design highlights two underlying principles. One principle is the rules' independence of each other and their equivalent status, exemplified in the separated and equal-sized boxes that are filled while constructing. Another principle involves the process of construction that affords creating and running partial solutions, while holding onto the bigger structure. This is supported on one hand by the modular nature of the construction board and on the other hand by providing the full problem space map from the start (e.g., two boxes or four boxes to be filled). In this section we test these claims, analyzing whether the children used these features (1) to *decompose* the problem into its parts; and (2) to gradually *build up* the solution from partial solutions. Evidence for the first is partial backtracking in debugging a program, instead of completely erasing and starting it anew—a move of *replacing* one rule among a group of previously used rules. Evidence for the second is a move of *addition*, adding more rules in successive constructions.

The first session is not included; it is based on a single condition-action couple and cannot be analyzed with respect to such moves. Each of the following 18 building sessions (three per child) is characterized by the observed transitions between constructions: *erasing* the previous program, *replacing* a rule, or, *adding* a rule. Each session could include more than one kind of move (Table 2).

Of the 18 sessions, 10 sessions (56%) included at least one "replace" transition; six (33%) included an "add" transition, three (7%) included completely erasing the program and starting again; two sessions included a single construction so that no transitions were involved and in one session some data was lost and could not be coded. It is interesting to note how these transitions pan out for the different sessions (Fig. 6). Erasing the whole program is infrequent and shows up mainly in an earlier session when it is also easier to re-create a new construction (only two boxes need to be filled). Most of the transitions involved replacing only one rule and their frequency is even across

Table 2 Moves between children's successive constructions

Transitions between successive constructions	Example
Erase the previous construction and start anew	[if pressed back; if unpressed turn] → [if pressed turn; if unpressed, forward]
Replace some but not all rules in the previous construction	[if pressed, move back; if unpressed, move forward] → [if pressed, turn; if unpressed, move forward]
Add rules onto a previous smaller set of rules	[if black, buzz; if white, don't buzz] → [if black, buzz; if white, don't buzz; if unpressed, forward]

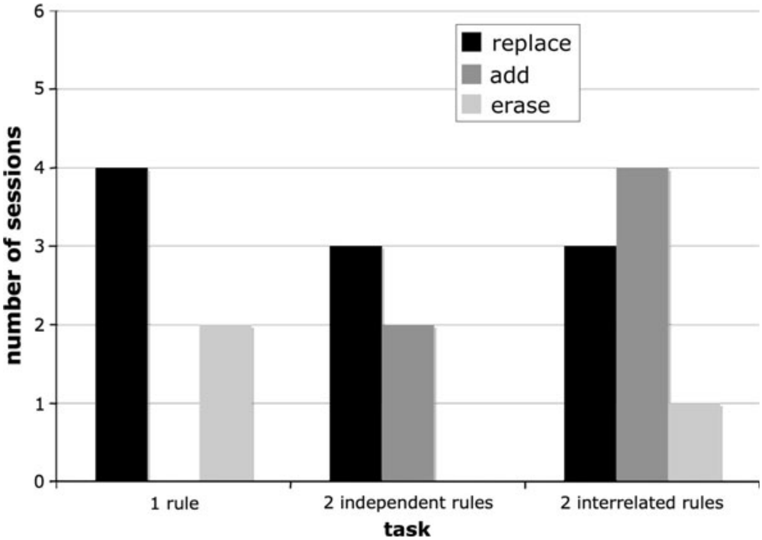

Fig. 6 Transitions among programs in a single session, typified as replacing a single rule, adding a rule or erasing the whole program and starting anew

tasks. The children added rules onto partial constructions only in the more complex sessions that involve four boxes, or four condition-action couples. Most of the children's moves between successive constructions utilized the proclaimed specific affordances of the RoboGan interface—the option to backtrack—by highlighting the parallel and independent nature of the rules, and the possibility to incrementally add onto the rules without losing the big picture, testing them as the construction gradually becomes more complex. As the tasks grew more complex, the latter feature was utilized more frequently.

4.1.4 Summary: What Do Children Do

Summarizing the children's activity in addressing the challenges of constructing a robot's emergent behaviors, they were mainly successful, solving this task within a relatively small number of debugging cycles that increased slightly with task complexity. As for scaffolds, the children required more adult support in the more complex tasks involving four condition-action couples and displayed developmentally advanced problem-solving behaviors that correspond with the interface affordances: when debugging their programs, they backtracked to partial solutions, and constructed the more complex behaviors in a modular fashion.

4.2 Research Question 2: What do Children Say (explain) About Their Construction of Artificial Adaptive Behaviors?

Findings are portrayed with respect to the children's understanding of the robot's behavior as rule-based, the complexity of their reasoning with rules and their understanding of the robot's behavior as emergent.

The following results illustrate the children's articulations of their performance in constructing the robot's behavior, explanations that were prompted at the conclusion of each activity. Only *spontaneous* responses are included.

In examining the children's verbal descriptions, we focus on three dimensions. Two relate to their reasoning with rules: the constructs they used (rules, scripts or episodes) and the complexity of their rules. A third dimension addresses children's understanding of the robot's behavior as *emergent*, by analyzing the description levels they employ: focus on the robot's behavior mechanistic building blocks (technological perspective) or on the its overall functioning framed as intentional behavior (psychological perspective). In presenting these results, we compare what the children *did* (Question 1) with what they *said*. In addition, we compare what they said about a robot's behavior that they *constructed* versus a robot's behavior that they did not create, but only *observed*. The latter comparison is central in its illumination of the role of construction for learning. However, we precede by stating a limitation to this comparison: the children first conducted an observation task and only later, a construction task, so that learning could have taken place in between the two events.

4.2.1 Understanding the Robot's Behavior as Rule-based

This section examines whether the children's explanations of their constructions is rule based. In the activities, the children constructed spatiotemporal events using a-temporal rules. These rules connect selected environmental features with particular actions. While the rule representation in the RoboGan interface assigns equal status to all rules, the resulting activation is not necessarily equally salient. In some cases, an activation of a rule is extremely brief, such as a barely perceptible swerve at the side, while crossing a winding bridge. Thus, the robot's overall behavior (comprising a sequence of successive actions) may be more prominent in the children's perception of its functioning rather than the behavior-generating rules themselves. In this section we ask whether the children's articulations catch up with the abstractness of the rules they had constructed to create the robot's behavior.

In a previous paper we have reported on these same children's use of rules when explaining *observed* robot behaviors (Mioduser et al. 2009). There, we presented a scale of abstraction to describe the children's articulations in terms of episodes (singular sequence of events), scripts (sequence of events that shows at least some repetition, usually upon encountering some triggering change in the environment) and rules (a-temporal set of condition-action couples). Definitions and examples of children's reference to these constructs are presented in Table 3. We had found that in their explanations of observed behaviors, in the earlier and simpler tasks the children used mainly rules. As the tasks advanced in complexity (the number of rules), the children shifted to the use of scripts, and episodes in the most difficult tasks. We use the same scale to describe the children's descriptions of the robot behaviors *they have constructed*, and then compare the two situations, to gauge the effect of construction on such explanations. Table 3 presents the coding scheme with examples selected from the children's descriptions.

We demonstrate these distinctions with a small event from the second construction session. Tim is observing a robot in action, a robot he has taught to avoid obstacles. In the process, he rearranges the obstacles and interacts with the robot—blocking its motion, and opening "gates" he has created. He is deeply engaged and does not respond to the interviewer's questions. He talks to himself, describing the robot's actions first as *episodes* and later as *scripts*. An *episode* type of description is seen as he joins the robot in the field,

Table 3 Coding scheme for children's articulations regarding the robot's behavior in terms of construct—rules, scripts and episodes

Construct	Definition	Examples
Episode	Description of a temporal sequence of events, momentary occurrences with no repetition or pattern	"Now he's on the bridge. He suddenly goes back, and then he starts going forward…"
Script	Description of a temporal sequence of events, which includes repeating series of occurrences, usually upon a triggering event, object or feature in the environment	"He's trying to go between the barriers. So he succeeds in getting through. He goes goes goes, he has a barrier, and so he turns and goes to the other side. He has another barrier, so he turns and goes to the other side. Then there's gate and there isn't a barrier"
Rule	Description in terms of a-temporal condition-action units	"He's simply moving and when he runs into something, it moves from it"

Table 4 Constructs in the children's explanations of the constructed robot's behavior

Task composition	Construct					
	Episode		Script		Rule	
	Explanation	Construction	Explanation	Construction	Explanation	Construction
Half a rule	0[a]	0	0	40	100	60
One rule	0	0	50	60	50	40
Two independent rules	14	0	57	0	29	100
Two interrelated rules	29	17	57	0	14	83

[a] Results are in percent (%), the proportion of children that responded by category in each session

places obstacles and rearranges them while the robot moves about: "He moves it [the obstacle]. He succeeded in knocking it down!" He is focused on the moment-to-moment event as it unfolds. Later on, as he observes a collision between the robot and a barrier he describes it in episode form: "He's going in [to the obstacle]… now he already got out. He already got out." At a later time in the same session, we hear him shift from an episode to a script: "[episode]: Here obstacles. Here an obstacle. A little one. Another obstacle. He won't be able to go through. [script]: When he reaches to every side, I'll put an obstacle. He won't be able to go through." In the first part, as before, he is focusing on the robot's voyage and its particularities. In the second part, the word "every" signifies an abstraction—while related to his own actions (he will block the robot whichever way it turns), the same sequence will happen in all directions—the robot reaches a side, gets blocked and cannot go through. The robot is trapped.

The children's constructs changed along the sequence of activities (Table 4). Earlier and simpler tasks elicit both rules and scripts, with rules dominating the more complex and later tasks.

4.2.2 Complexity in Reasoning with Rules

In the previous section we have seen the children's tendency to reason with rules increasing throughout the experimental period. Abstraction of the a-temporal rules is only one component of the challenge; as the sessions advanced, the children were also challenged with tasks requiring working with a greater number of rules. In this section, the complexity of the children's explanations is explored. We examine their unassisted descriptions of the robot's behavior they had constructed that took place at the end of each session.

When the children used rules, their explanations were coded for the number of condition-action couples, ranging from half a rule (one condition-action couple) to two interrelated rules (four condition-action couples). For example, a child has constructed a bridge-crossing robot. The bridge is a black winding path on the background of white. She has constructed this behavior with four condition-action couples (see Appendix). At the summation of the activity, she describes the robot: "… When he's on the white he goes to the black, and when he's on the black, he continues going". This is coded as one rule or two condition-action couples: if [on white], then [go to black]; if [on black], then [keep going].

The number of rules the children incorporated in a single explanation of a behavior they had *constructed* is described in Fig. 7, alongside with (a) the task's rule composition (that is, what they had already succeeded in constructing); and (b) the children's spontaneous descriptions of *observed* robot behaviors.

As the tasks become more complex the children incorporated more rules into their explanations. These rules begin with the task-appropriate one condition-action couple (half a rule) in the first task. They cap at almost two condition-action couples in the more complex later tasks. This limit falls one rule short of the full complexity of these tasks (four condition-action couples or two rules). Thus, there is a one-rule gap between what they *did* and what they *said* about what they did. In a parallel paper, we describe their strategies in reducing the complexity of their constructions in terms they can articulate: "pruning" involved ignoring part of the logical structure and focusing on another; "fusing" involved coalescing several rules or functions into one (Levy and Mioduser 2010).

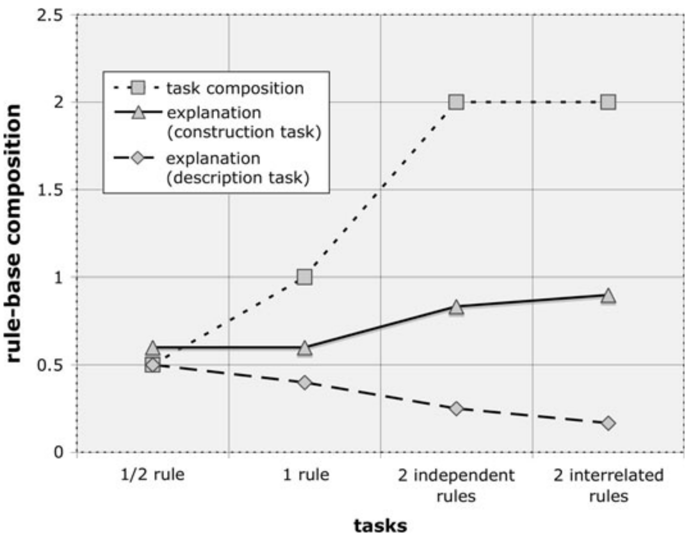

Fig. 7 Mean number of rules in the children's explanations of their programmed robot's behavior, compared with the task composition (what they had programmed) and their explanations of a demonstrated robot's behavior

This progression is contrary to what was found in the same children's explanations of an observed robot's behavior ("description tasks"), where the later and more complex tasks showed reduced abstraction and a shift to temporal constructs. The two contradictory progressions regarding rule-based reasoning—for observed and constructed robot behaviors—point to the privileged role of construction in supporting this form of reasoning. The demonstrated shift from temporal to a-temporal rule-based reasoning about the system is associated with the activity of constructing with rules, this effect becoming more pronounced with experience and with the more complex tasks. The very activity of constructing robot behaviors helped the children transition to the use of rules even when they could not articulate their full complexity, their articulations shifting up for the more complex tasks by almost one rule or two condition-action couples.

The progression for the children's explanations of the observed robot behaviors supports what is reported in early developmental literature regarding children's tendency to organize their reasoning in terms of scripts (Flavell et al. 1993) and limits to their reasoning with rules (Siegler and Chen 1998). However, the progression for the children's descriptions of the constructed robot behaviors runs contrary to this same literature. Constructing real tangible behaviors with rules and their physical exploration helps children go beyond their expected cognitive abilities, displaying more mature forms of reasoning.

4.2.3 Understanding the Robot's Behavior as Emergent

Do the children view the behaviors they constructed as emergent? In this study, we look into this question through two angles—one is a "levels" perspective and the other relating to how rules play into action.

The children's explanations at the end of each session were examined at two distinct levels (Wilensky and Resnick 1999): the causal and the emergent levels. The robot's parts, mechanisms and programming rules together with the features of its environment constitute the *underlying causal level*. In fact, the environment can be viewed as several non-moving agents in a multi-agent system (Bar-Yam 1997), where the robot is a single moving agent. The local interactions between these agents result from the instantiation of the specific rules. The gestalt of these instantiations in the environment can be viewed as the robot's overall behavior—the *emergent level*. This emergent behavior results from a combination of: (a) the physical components at the lower level, the mechanisms that support the robot's particular actions, e.g., navigation or lifting loads; (b) the rules of interaction between the environment and the robot, e.g., upon hitting an object—turn; and (c) the environment itself, whether and where there are objects or features in the environment that the robot can perceive.

For example, a system can include a navigating robot with a light sensor that distinguishes between light and dark areas (Fig. 8). This robot can be programmed to turn on dark and move forth on light. It can move through an environment that is shaped like a checkerboard, each square only slightly larger than the robot's span of motion upon turning. Its emergent behavior can be described as "*searching for dark squares*": the robot moves across the white squares, hovering upon the black ones, turning on them until its sensor moves out and it sets off again on its journey.

Each of the above three components can be varied singly or in combination, resulting in different overall behaviors: e.g., if the robot were lifting weights rather than moving through space; if the rules were slightly changed (e.g., exchanging between light and dark as the condition part of the rule); or the environment was a different one (e.g., instead of a checkerboard, a large light island on a dark background).

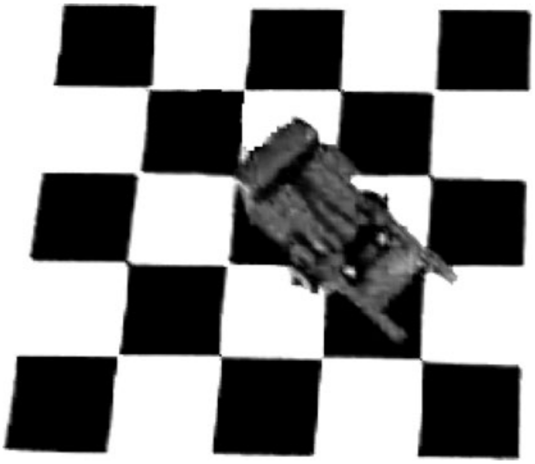

Fig. 8 Robot on checkerboard "searching" for black squares

In our previous work with the same children (Levy and Mioduser 2008) we explored the children's explanatory frameworks as they described a demonstrated robot behavior, focusing on two frameworks—an intentional "psychological" form of explanation versus a technological one, explaining the robot's behavior as resulting from its parts and rules. These two frameworks map onto the two levels of description portrayed above: the "psychological" framework maps onto the robot's emergent behavior; the "technological" framework maps onto the level underlying and constituting the distributed causes for this behavior. In exploring the children's descriptions of the robot's behavior, we had found that the children were relatively consistent in operating within one of two modes of explanation: an "engineering" mode describing only the mechanistic level; and a "bridging" mode, which aligns and relates the two levels of description. With increase in task difficulty, the children showed us less of the purely engineering mode and more of that bridging the two frameworks or description levels.

Here we return to this question in the context of building, with the goal of examining the impact of constructing the robot's behaviors on the children's understanding of the system as emergent, distinguishing and relating the two levels of description. To support comparison with the previous results, we retain the original terms for the two levels: "psychological", "technological" and "combined" (see coding in Table 5). The children's explanations at the end of each task were analyzed with respect to this coding scheme and the group results are presented in Fig. 9.

As the task complexity increases, some of the children shift from a psychological to a technological perspective. This runs contrary to what was found for the children's spontaneous explanations in the observation tasks, where increased task difficulty was associated with less technological explanations. However, the children spoke mainly of one level—either behavioral or mechanistic, but not both. This is distinct from their explanations in the observation tasks, for which some of the children consistently provided descriptions that combined and related behavioral and mechanistic levels of description.

4.2.4 Summary: What Do Children Say about What They Did

Children's explanations following the process of constructing robot behaviors are indicative of the clear contribution of this experience to their conceptions and understanding.

Table 5 Coding scheme for children's articulations regarding the robot in terms of levels or frameworks—mechanistic, behavioral or combined

Perspective	Definition	Example
Technological	Robot's parts, mechanisms and rules constitute the framework in describing the robot	He's simply moving, and when he runs into something, it [robot] moves from it [something]
Psychological	Robot's behavior, described in functional and intentional terms constitute the framework for describing the robot	Ohhhh, he's afraid of the light, runs away from the light It will try to run away from all these obstacles
Combined	Both technological and psychological perspectives are included in a description of the robot, related and aligned	"So he can turn first, so that he won't see the light all the time and he'll always look at the side that has dark"

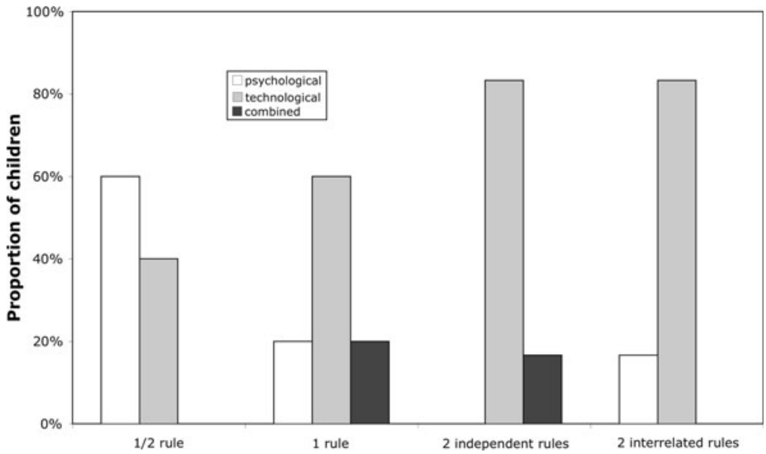

Fig. 9 Explanatory frameworks in the children's explanations of their constructed robot's behavior

The level of complexity of their explanations (measured as number of rules the children incorporated in a single explanation of a behavior they had constructed) increased with the complexity of the tasks. This conflicts with the findings for the observation tasks, where in the later and more complex tasks the children showed reduced abstraction and a shift to temporal constructs (e.g., events or scripts). However, children were able to do more than what they were able to say about what they did—a gap of about one rule (two condition/action couples) was observed between the complexity of the behaviors they constructed and the explanations following the construction.

Contrasting paths were also found between observation and construction tasks with regards to the children's conceptual approach, whether it was focused on causal relationships between particular components (technological perspective) or on the overall emergent behavior (psychological perspective). As complexity increased, in observation tasks children tended to use either a psychological or a combined perspective. In contrast, in construction tasks the path led clearly towards a technological perspective. While involved in constructing the robot's behavior the children were acquainted with and focused on the particular causal relationships, on the contribution of different parts and mechanisms to its overall behavior.

5 Conclusion

This study set out to explore young children's ability to construct and explain increasingly sophisticated adaptive behaviors of a behaving artifact, an autonomous robot. To this goal, we had developed the RoboGan software that was planned to support their construction of temporal emergent behaviors with an a-temporal rule structure.

Before discussing the conclusions from this investigation, we state some qualifications based on its limitations. One limitation is the small sample size—six children. The second is that the children described the demonstrated robot behaviors before constructing them, so that comparing their explanations for the two tasks may be confounded with learning. In future research, separation between the two tasks (i.e., conducting only description or construction tasks and comparing between them) could resolve this confound.

Several conclusions follow from this study.

One conclusion concerns the question of whether young children can imagine, plan and construct adaptive robot behaviors that take place in space over time with abstract a-temporal rules. The challenge of constructing such emergent behaviors is notoriously hard. In the field of engineering education, many high school and undergraduate students are less successful at creating such autonomous robot behaviors and resort mainly to online user controlled behaviors (Bilotta and Pantano 2000; Fagin and Merkle 2002; Kelleher and Pausch 2005). In the domain of complex systems, understanding such behaviors requires an "emergent schema", a way of explaining coherent global patterns based on a small set of simple rules that describe the ongoing local interactions between objects (Bar-Yam 1997). It is proposed that understanding an adaptive robot falls into a similar schema of emergence, where no simple reduction of the overall behavior pattern is possible. Several studies report older students' difficulties in grappling with the emergent schema (Chi 2005; Jacobson 2001). Chi (2005) has proposed that direct intervention would be beneficial to helping people incorporate such a schema to their repertoire of possible causal structures and Slotta and Chi (2006) have demonstrated the utility of such interventions. Several learning environments and designs have shown success in supporting students' growing understanding of complex systems through constructing models (Klopfer 2003; Resnick and Wilensky 1993; Wilensky and Reisman 2006), participating in simulations (Klopfer et al. 2005; Resnick and Wilensky 1998; Soloway et al. 2001) and exploring given models (Levy and Wilensky 2009). Building upon these studies, we wish to contribute another important facet in supporting such learning: the developmental aspect. *When is the best time to help people construct new schemas?* In the literature review, we have described how children at five-to-seven years of age are transitioning into a deeper understanding of computational intelligent artifacts, relating their mindful character to their inanimate status (van Duuren and Scaife 1995, 1996). A more general developmental achievement relates to understanding causality in physical systems. Several studies have demonstrated that during these years, one can observe a shift in understanding causality from a global-functional framework to one that searches for specific local trains of cause-and-effect in the components of the system (Piaget 1956; Metz 1991; Lehrer and Schauble 1998). It would seem that during this sensitive time, it would be most opportune to support children in creating alternative schemas of causality, rather than locking into a single schema of a "direct" chain of sequential cause-and-effect links. Given the centrality of the emergent schema in making sense of many systemic phenomena in our world, we advocate the importance of creating such learning situations as those depicted in the current study *specifically for young children during the five-to-seven years of age transitional time.*

Going back to children's understanding of how spatiotemporal behaviors result from a-temporal rules, it is important to note that these rules are distinct from the kinds of rules explored in previous developmental research (Siegler and Chen 1998; Frye et al. 1996), such as "in a balance scale, the heavier side will go down" in at least two ways. One distinction is that these rules describe a process rather than an end state: the rules interact with the particular environment that is continually changing, and from these interactions the observed behaviors arise. A second distinction is in salience: the robot's control rules are not necessarily observable, as activation of some rules can be extremely brief, such as turning away from an obstacle before moving on through the terrain. Both of these distinctions point to the greater challenge in relating rules to the system's overall behavior. Thus, based on the above cited literature on children's reasoning with rules, one would expect their performance to be less sophisticated than that demonstrated by these previous studies. However, we have found that the children were surprisingly successful in creating rule-based adaptive robot behaviors. Moreover, they solved the tasks in a relatively small number of cycles that increased slightly with task complexity. In constructing the robot's behaviors they used strategies uncommon among young children (e.g., Klahr 1985 on young children's avoidance of backtracking in solving problems) that involved decomposing the problem and constructing it modularly, as well as backtracking only partially to repair components of the program. One may conclude from these results that in appropriate situations, young children are well-oriented to "thinking with rules"—when they are reasoning about concrete objects and events that involve construction and interactive exploration with appropriate supports. Both in constructing with and articulating their constructions, the children have shown us that they can go beyond normative developmental constraints (e.g., Kuhn 1989). It would seem that embedding such abstractions in concrete objects and events, easy to manipulate, explore and interact with, supports children's reasoning and abilities beyond their expected abilities.

In this study, we have seen the interaction between developmental constraints and environmental supports. These supports included an adult's assistance and the spatial scaffolding in the RoboGan interfaces. Adult assistance was necessary for the more complex tasks that involved four condition-action couples. This assistance involved pointing out relevant features in the environment and the robot's actions and helping the child decompose the more sophisticated problems. We have found that the one-rule structure comprised of two condition-action couples was transitional: some children articulated and constructed such structures independently, while others required adult support. We have also found that when the problem consisted of four condition-action couples, the children turned to a more modular form of behavior construction—testing partial solutions and adding onto them. They utilized the RoboGan's spatial scaffolding to approach the task within the limits of what they can do on their own, and then stretched themselves beyond these limits by gradually filling in the map of the problem space. We had already seen that two condition-action couples were the limit of the children's independent explanations for observation tasks, in which the children are not programming the robot (Mioduser et al. 2009). Knowing this, one may plan appropriate support for children in school settings—knowing what they can do on their own, and when they might need support; moreover, given the gap of one rule between what they can say and what they can do, we now know that with such support the children can go beyond their articulations. One interesting conclusion results from comparing the children's descriptions of an *observed* robot behavior with those of a robot for which they had *constructed* its behavior. When looking into their explanatory frameworks, it was found that for the observation challenge, three of the children separated and coordinated an intentional and an engineering point of view. However, these very same children used mainly an engineering point of view when describing their constructions. It does make sense that when engaged in constructing with the technological programming tools, they would be focused on these very tools with which they construct. However, the importance of separating and coordinating the two views is necessary for a more sophisticated understanding of such computational artifacts (Ackermann 1991), as well as understanding emergence in terms of micro- and macro-levels in the system (Wilensky and Resnick 1999). Thus, one may conclude that *incorporating different kinds of tasks in the learning environment*—both *construction* challenges, aimed at engaging the child into a deep understanding of how such systems work, and *observation* tasks, targeting a more detached point of view that combines with such deep understanding are necessary for a comprehensive understanding of the system. These two activities map onto Ackerman's (1996) view combining "diving in" and "stepping out" modes, both essential to understanding a system. Further interventions, such as elicitation and settings that involve more participants may help children voice and discuss their more sophisticated understandings. In addition, it would be interesting to see whether increasing the range of choices in constructing behaviors would contribute to the children's versatility in reasoning with rules or would overload their capacity to do so.

One of the important conclusions in this study is the specific contribution of construction to the children's understanding of adaptive systems. We have compared the children descriptions of demonstrated robot behaviors with their explanations of behaviors they had constructed themselves. The two were distinct across several dimensions. One dimension involves whether the explanations were rule-based—the abstract rule structure was dominant, especially in the more complex tasks, for the constructed but not for the demonstrated behaviors. A second dimension concerns the complexity of their constructions and explanations that increases with complexity for construction but not for demonstrated behaviors. A third dimension describes the explanatory frameworks the children used—while for the more complex demonstrated behaviors the children employed intentional or combined mechanistic/intentional explanations, they employed mainly mechanistic explanations for their constructions. These three distinctions point to the privileged status of construction to a deeper understanding of such systems—increasing the abstractness of their constructs in reasoning about the system, involving greater complexity in such reasoning and a focus on the mechanistic building blocks of the system, developing an "engineering" or designer's view of robot's behavior.

Based on these conclusions, we wish to proponent the importance of behavior construction learning environments (building sense), such as the RoboGan, to children's evolving understanding of adaptive intelligent artifacts and the intellectual structures underlying their behavior (making sense).

Acknowledgments We gratefully thank Dr. Vadim Talis, who collaborated with us in designing the RoboGan environment and in conducting the research with the children.

Appendix

See Table 6.

Table 6 Description and construction tasks

Rule-base configuration	Task	Description	Construction
Half a rule	Behavior	*…coming, coming out!* The robot is cowering inside a dark cave. A flashlight is placed above its nose and it gingerly follows it out of the cave. Once reaching the entrance, it struts out independently, disregarding the flashlight, its path tracing a straight line.	*Scaredy-cat* Teach the robot to be afraid of the flashlight The children may choose to have the robot avert its "face" when a flashlight is placed in front of it. Alternatively, they can have the robot retreat upon confronting the flashlight.
	Environment	Dark cave, lighted surroundings, a flashlight	A flashlight
	Robot structure	A light sensor facing upwards, distinguishes light from dark	A light sensor is facing upwards, distinguishes the luminosity of the flashlight, from that of the environment
	Rules	When the light sensor sees light, go forward When the light sensor sees dark, don't move	When the light sensor sees dark, stay put (automatically programmed) When the light sensor sees light, either turn (avert) or go backwards (retreat)
One rule	Behavior	*Guarding an island* The robot is placed upon an island. The robot moves across the island until it reaches its edge. It then travels around the perimeter of the island, its "nose" sniffing and following the island's rim	*Seeking freedom* Program the robot so it can move freely in an obstacles field The robot roams about the field, ramming into obstacles and extricating itself, while changing its heading
	Environment	A light colored island (white paper) on the background of a dark-colored rug	A walled board, with several barriers scattered throughout
	Robot structure	A light sensor facing down, distinguishes light from dark	A touch sensor facing forwards, it is un-pressed until it reaches a wall and then becomes pressed
	Rules	When the light sensor sees light, go forward When the light sensor sees dark, turn to the left	When the touch sensor is pressed, turn to the left or to the right When the touch sensor is un-pressed, go forward
Two independent rules	Behavior	*Brightening dark holes, oops! trapped by a hat…* A hatless robot travels through a landscape splattered with dark spots, flashing its light when it reaches a dark spot. However, when a hat is placed on its head, it turns like a top	*The flight of the flower-seeking bee* The robot is now a bee. Teach the robot-bee fly through a field without getting trapped in the rocks. Help it find flowers and notify its friends of the discovery, so they can come along and enjoy them as well The bee-robot navigates a field, extracting itself when it hits a rock. When it finds flowers it calls out to its friends

Table 6 continued

Rule-base configuration	Task	Description	Construction
	Environment	Dark spots are scattered through a light-colored terrain A hat	A light colored board is "planted" with dark flowers and several barriers/rocks are scattered about
	Robot structure	A touch sensor faces upwards, is depressed when a hat is placed on top of the robot A light sensor faces downwards, distinguishing dark from light	A touch sensor faces forward, and is depressed when the robot hits a barrier A light sensor faces downwards, distinguishing dark from light
	Rules	When the touch sensor is pressed, turn left. When it is un-pressed, go straight When the light sensor sees dark, flash. When the light sensor sees light, don't flash	When the touch sensor is pressed, turn left or right. When it is un-pressed, go straight When the light sensor sees dark, buzz. When the light sensor sees light, don't buzz
Two interrelated rules	Behavior	*The cat in the hat likes black* The robot navigates across a large checkerboard. When the robot wears a hat, it searches for the black squares, homing in on them. It quickly moves across the white squares, turning for a while on a black square, before leaving it and homing in on the next black square When the robot is not wearing a hat, it moves across the board in a straight line, irrespective of the colors below	*Crossing a long and winding bridge* Program the robot to traverse a winding bridge, without falling off into the turbulent water flowing below. The robot starts out at one end of the bridge, tracing a jagged route as it heads forward, reaches the edges of the bridge and turns away. When it reaches the end of the bridge, it can stop, continue straight or turn around
	Environment	Large checkerboard made up of black and white squares. A hat	A black winding strip against a white background
	Robot structure	A touch sensor faces upwards, and is depressed when a hat is placed on top of the robot A light sensor faces downwards, distinguishing dark from light	Two light sensors are facing down, side-by-side. They distinguish light from dark
	Rules	When the touch sensor is depressed and the light sensor sees dark or light, move forward When the touch sensor is un-pressed, and when the light sensor sees black, move backwards When the touch sensor is un-pressed and the light sensor sees light, turn to the right	When both light sensors see black, go forward When the right light sensor sees black and the left light sensor sees white, turn to the right When the right light sensor sees white and the left light sensor sees white, turn to the left When both light sensors see white, then either stop, go straight, turn right or left

References

Ackermann, E. (1991). The agency model of transactions: Towards an understanding of children's theory of control. In J. Montangero & A. Tryphon (Eds.), *Psychologie genetique et sciences cognitives*. Geneva: Fondation Archives Jean Piaget.

Ackermann, E. (1996). Perspective-taking and object construction. In Y. Kafai & M. Resnick (Eds.), *Constuctionism in practice: Designing, thinking, and learning in a digital world* (pp. 25–37). Mahwah, NJ: Lawrence Erlbaum Associates.

Bar-Yam, Y. (1997). *Dynamics of complex systems, The Advanced Book Program*. Reading, MA: Addison-Wesley.

Begel, A. (1996). *LogoBlocks: A graphical programming language for interacting with the world*. Cambridge, MA: Electrical Engineering and Computer Science Department. MIT.

Bernestein, D., & Crowley, K. (2008). Searching for signs if intelligent life: An investigation of young children's' beliefs about robot intelligence. *Journal of the Learning Sciences, 17*, 225–257.

Bers, M. U., & Portsmore, M. (2005). Teaching partnerships: Early childhood and engineering student teaching math and science through robotics. *Journal of Science Education and Technology, 14*(1), 59–73.

Bilotta, E., & Pantano, P. (2000). Some problems of programming in robotics. In A. Blackwell & E. Bilotta (Eds.), *Proceedings of PPIG 12*. Italy: Cozenza.

Bloom, P. (1996). Intention, history, and artifact concepts. *Cognition, 60*, 1–29.

Chi, M. T. H. (2005). Commonsense conceptions of emergent processes: Why some misconceptions are robust. *Journal of the Learning Sciences, 14*(2), 161–199.

Clements, D. (1990). Metacomponential development in a logo programming environment. *Journal of Educational Psychology, 82*(1), 141–149.

Clements, D. (1999). The future of educational computing research: The case of computer programming. *Information Technology in Childhood Education, 1*, 147–179.

Cuban, L. (1993). Computers meet classroom: Classroom wins. *The Teachers College Record, 95*(2), 185–210.

Defeyter, G. (2003). Acquiring an understanding of design: Evidence from children's insight problem solving. *Cognition, 89*, 133–155.

Diesendruck, G., Hammer, R., & Catz, O. (2003). Mapping the similarity space of children's and adults' artifact categories. *Cognitive Development, 18*, 217–231.

Fagin, B., & Merkle, L. (2002). Quantitative analysis of the effects of robots on introductory computer science education. *ACM Journal of Educational Resources in Computing, 2*(4), 1–18.

Flavell, J. H., Miller, P. H., & Miller, S. A. (1993). *Cognitive Development* (Third ed.). New Jersey: Prentice Hall.

Frye, D., Zelazo, P. D., Brooks, P. J., & Samuels, M. C. (1996). Inference and action in early causal reasoning. *Developmental Psychology, 32*(1), 120–131.

Fujita, M., Kitano, H., & Doi, T. T. (2000). Robot entertainment. In A. Druin & J. Hendler (Eds.), *Robots for kids: Exploring new technologies for learning* (pp. 37–72). San-Francisco, California: Morgan Kaufmann Publishers.

Gelman, S. A., & Opfer, J. E. (2004). Development of the Animate-Inanimate Distinction. In U. Gowwami (Ed.), *Blackwell handbook of childhood cognitive development*. London: Wiley-Blackwell.

Granott, N. (1991). Puzzled minds and weird creatures: Phases in the spontaneous process of knowledge construction. In I. Harel & S. Papert (Eds.), *Constructionism* (pp. 295–310). Norwood, NJ: Ablex Publishing Corporation.

Horn, M., Solovey, E., Crouser, R., & Jacob, R. (2009). *Comparing the use of tangible and graphical programming languages for informal science education. Proceedings of CHI 2009*. Boston, MA: ACM.

Jacobson, M. J. (2001). Problem solving, cognition, and complex systems: Differences between experts and novices. *Complexity, 6*(3), 41–49.

Jipson, J. L., & Gelman, S. A. (2007). Robots and rodents: Children's inferences about living and nonliving kinds. *Child Development, 78*(6), 1675–1688.

Jonassen, D. H. (Ed.). (2004). *Handbook of research on educational communications and technology* (2nd ed.). Mahwah, NJ: Lawrence Erlbaum Associates.

Kahn, K. (2004). ToonTalk—steps towards ideal computer-based learning environments. In M. Tokoro & L. Steels (Eds.), *A learning zone of one's own: Sharing representations and flow in collaborative learning environments* (pp. 259–270). Amsterdam, The Netherlands: IOS Press Inc.

Kelleher, C., & Pausch, R. (2005). Lowering the barriers to programming. *ACM Computing Surveys, 37*(2), 83–137.

Kemler Nelson, D. G., & 11 Swarthmore College Students. (1995). Principle-based inferences in young children's categorization: Revisiting the impact of function on the naming of artifacts. *Cognitive Development, 10*, 347–380.

Klahr, D. (1985). Solving problems with ambiguous subgoal ordering: Preschoolers' performance. *Child Development, 56*, 940–952.

Klahr, D., Fay, A. L., & Dunbar, K. (1993). Heuristics for scientific experimentation: A developmental study. *Cognitive Psychology, 25*, 111–146.

Klopfer, E. (2003). Technologies to support the creation of complex systems models—using StarLogo software with students. *Biosystems, 71*(1–2), 111–122.

Klopfer, E., Yoon, S., & Perry, J. (2005). Using palm technology in participatory simulations of complex systems: A new take on ubiquitous and accessible mobile computing. *Journal of Science Education and Technology, 14*(3), 285–297.

Kuhn, D. (1989). Children and adults as intuitive scientists. *Psychological Review, 96*, 674–689.

Lehrer, R., & Schauble, L. (1998). Reasoning about structure and function: Children's conceptions of gears. *Journal of Research in Science Teaching, 35*(1), 3–25.

Levy, S., & Mioduser, D. (2008). Does it "want" or "was it programmed to…"? Kindergarten children's explanations of an autonomous robot's adaptive functioning. *International Journal of Technology and Design Education, 18*(3), 337–359.

Levy, S., & Mioduser, D. (2010). Approaching complexity through planful play: Kindergarten children's strategies in constructing an autonomous robot's behavior. *International Journal of Computers in Mathematical Learning, 15*(1), 21–43.

Levy, S. T., & Wilensky, U. (2009). Students' learning with the connected chemistry (CC1) curriculum: Navigating the complexities of the particulate world. *Journal of Science Education and Technology, 18*(3), 243–254.

Macchiusi, L. (1997). Children, robotics and problem solving: Technology in the early childhood classroom. *Australian Educational Computing, 12*(2), 24–31.

Maddocks, R. (2000). Bolts from the blue: How large dreams can become real products. In A. Druin & J. Hendler (Eds.), *Robots for kids: Exploring new technologies for learning* (pp. 111–156). San-Francisco, California: Morgan Kaufmann Publishers.

Matan, A., & Carey, S. (2001). Developmental changes within the core of artifact concept. *Cognition, 78*, 1–26.

Metz, K. (1991). Development of explanation: Incremental and fundamental change in children's physical knowledge. *Journal of Research in Science Teaching, 28*(9), 785–797.

Mioduser, D., Levy, S. T., & Talis, V. (2009). Episodes to scripts to rules: Concrete-abstractions in kindergarten children's explanations of a robot's behaviors. *Journal of Technology and Design Education, 19*(1), 15–36.

Monroy-Hernandez, A., & Resnick, M. (2008). Empowering kids to create and share programmable media. *Interactions, 15*(2), 50–53.

Montemayor, J., Druin, A., & Hendler, J. (2000). PETS: A personal electronic teller of stories. In A. Druin & J. Hendler (Eds.), *Robots for kids: Exploring new technologies for learning* (pp. 73–110). San-Francisco, California: Morgan Kaufmann Publishers.

Morgado, L., Cruz, M., & Kahn, K. (2006). Radia Perlman—A pioneer of young children computer programming. In A. Mendez-Vilas, S. Martin, J. Mesa-Gonzalez, & J. A. Mesa-Gonzalez (Eds.), *Current developments in technology-assisted education*. Proceedings of m-ICTE 2006 (pp. 1903–1908). Badajoz, Spain: Formatex.

Okita, S. Y., & Schwartz, D. L. (2006). Young children's understanding of animacy and entertainment robots. *International Journal of Humanoid Robotics, 3*(3), 393–412.

Papert, S. (1980/1993). *Mindstorms: Children, computers, and powerful ideas* (1st and 2nd ed.). Cambridge, MA: Basic Books.

Papert, S. (1987). Computer criticism vs. technocentric thinking. *Educational Researcher, 16*(1), 22–30.

Papert, S., & Solomon, C. (1971). *Twenty things to do with a computer. Artificial Intelligence Memo No. 248, Logo Memo No. 3*. Cambridge, MA: MIT.

Pea, R. D., Kurland, D. M., & Hawkins, J. (1985). Logo and the development of thinking skills. In M. Chen & W. Paisley (Eds.), *Children and microcomputers: Formative studies* (pp. 193–212). Beverly Hills, CA: Sage.

Perlman, R. (1974). *TORTIS—toddlers own recursive turtle interpreter system. A.I. Memo 311 - Logo Memo 9*. Cambridge, MA: MIT A.I. Lab.

Piaget, J. (1956). *The child's conception of physical causality*. New Jersey: Littlefield Adams and Co.

Piaget, J., & Inhelder, B. (1972). *Explanations of Machines. The Child's conception of physical causality* (pp. 195–236). New-Jersey: Littlefield Adams and Co.

Resnick, M. (1998). Technologies for lifelong kindergarten. *Educational Technology Research and Development, 46*(4), 43–55.
Resnick, M. & Wilensky, U. (1993). *Beyond the deterministic, centralized mindsets: New thinking for new sciences*. Paper presented at the annual meeting of the American Educational Research Association, Atlanta, GA.
Resnick, M., & Wilensky, U. (1998). Diving into complexity: Developing probabilistic decentralized thinking through role-playing activities. *The Journal of the Learning Sciences, 7*, 153–172.
Scaife, M., & van Duuren, M. (1995). Do computers have brains? What children believe about intelligent artefacts. *British Journal of Developmental Psychology, 13*, 367–377.
Schauble, L. (1990). Belief revision in children: The role of prior knowledge and strategies for generating evidence. *Journal of Experimental Child Psychology, 49*, 31–57.
Schweikardt, E., & Gross, M. (2007). *A brief survey of distributed computational toys*. Proceedings of the first IEEE international workshop on digital game and intelligent toy enhanced learning (DIGITEL'07), pp. 57–64.
Siegler, R. S. (1986). *Children's thinking*. Englewood-Cliffs, NJ: Prentice-Hall International.
Siegler, R. S., & Chen, Z. (1998). Developmental differences in rule learning: A microgenetic analysis. *Cognitive Psychology, 36*, 273–310.
Slotta, J. D., & Chi, M. T. H. (2006). Helping students understand challenging topics in science through ontology training. *Cognition and Instruction, 24*(2), 261–289.
Sobel, D. M., Tenenbaum, J. B., & Gopnik, A. (2004). Children's causal inferences from indirect evidence: Backwards blocking and Bayesian reasoning in preschoolers. *Cognitive Science, 28*, 303–333.
Soloway, E., Norris, C., Blumenfeld, P., Fishman, B., Kracjik, J., & Marx, R. (2001). Log on education handheld devices are ready-at-hand. *Communications of the ACM, 44*, 6.
Turkle, S. (1984). *The second self: Computers and the human spirit*. New York: Simon and Schuster.
van Duuren, M. A., & Scaife, M. (1995). How do children represent intelligent technology? *European Journal of Psychology of Education, 10*, 289–301.
van Duuren, M., & Scaife, M. (1996). Because a robot's brain hasn't got a brain, it just controls itself: Children's attribution of brain related behavior to intelligent artifacts. *European Journal of Psychology of Education, 11*(4), 365–376.
Wilensky, U., & Reisman, K. (2006). Thinking like a wolf, a sheep or a firefly: Learning biology through constructing and testing computational theories—an embodied modeling approach. *Cognition & Instruction, 24*(2), 171–209.
Wilensky, U., & Resnick, M. (1999). Thinking in levels: A dynamic systems perspective to making sense of the world. *Journal of Science Education and Technology, 8*(1), 3–19.
Wyeth, P., & Purchase, H. (2000). *Programming without a computer: A new interface for children under eight*. Proceedings of the first australasian user interface conference, p. 141, Australia. Retrieved at: http://www.cl.cam.ac.uk/users/afb21/CognitiveDimensions/workshop2005/Wright_draft_paper.pdf.
Yelland, N. (1995). Mindstorms or a storm in a teacup? A review of research with Logo. *International Journal of Mathematics Education Science and Technology, 26*(6), 853–869.
Zuckerman, O., Arida, S., & Resnick, M. (2005). *Extending tangible interfaces for education: Digital Montessori-inspired manipulatives*. Proceedings of CHI 2005. ACM Press, pp. 859–868.