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Does it ''want'' or ''was it programmed to...''? Kindergarten children's explanations of an autonomous robot's adaptive functioning

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Abstract This study investigates young children's perspectives in explaining a self-regulating mobile robot, as they learn to program its behaviors from rules. We explore their descriptions of a robot in action to determine the nature of their explanatory frameworks: psychological or technological. We have also studied the role of an adult's intervention in their reasoning. The study was conducted individually with six kindergarten children along five sessions that included tasks, ordered by increasing difficulty. We developed and used a robotic control interface. We have found that the children employed two modes of explanation: ''engineering'' mode focused on the technological building blocks which make up the robot's operation; ''bridging'' mode tended to combine and align two explanatory frameworks – technological and psychological. However, this was not consistent across tasks. In the easiest tasks, involving one condition–action rule, most of the children used a technological perspective. When the task became more difficult, most children shifted to a psychological perspective. Further experience in programming was associated with a shift to technological or combined explanatory frameworks. The results are discussed with respect to developmental literature on children's explanatory frameworks, and with regard to educational implications of incorporating such learning environments in early childhood classes.

Keywords Robotics concepts · Preschool education · Programming · Explanatory framework · Technology education

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Controlled self-regulated systems pervade our daily environment, embodying central concepts related to systems, adaptation and emergence. Robotic systems, which have been part of educational settings for over two decades, provide opportunities to *interact* with, and *construct* controlled adaptive behaviors (Papert 1980/1993; Resnick and Martin 1991; Mioduser et al. 1996; Fujita et al. 2000; Montemayor et al. 2000; Wyeth and Purchase 2000; Morgado et al. 2001; Talis 2002; Bers and Portsmore 2005). This paper reports on a study conducted to explore young children's evolving understanding of the functioning of a self-regulated adapting robot. We investigated the children's understanding through a sequence of observations and interviews, analyzing the children's expressed ideas in terms of the explanatory frameworks framing their perceptions of the functional and computational aspects of the artifacts under consideration.

Research concerning young children's perception and learning of technological systems is sparse (Zuga 2004). While several studies have explored young children's perception of technology (Jarvis and Rennie 1998) and investigated the processes by which they plan, create and relate to their designed objects (Fleer 1999, 2000; Carr, 2000), little research has been conducted into their conceptual understanding and learning of a more focused set of technological constructs. Through this study, we hope to contribute to the evolving body of research in the technology education field, dealing with young children's conceptual understanding of central ideas regarding adaptive technological systems.

How many times have you uttered expletives at your computer when it crashes or produces unanticipated actions? We know for sure the computer is not alive, and yet... Such behaving artifacts teeter precariously between the animate and inanimate world. Through their actions, but especially their intelligent behavior, the inanimate world is brought closer to the living. Even the realms within which such systems are studied and developed are often named to bridge the chasm between the domains, such as Artificial Intelligence or Artificial Life (Resnick and Martin 1991).

What conceptual perspectives guide children's thinking about behaving robots? Turkle (1984) and Ackermann (1991) speak of two distinct frameworks for approaching the artificial world: the *psychological* and the physical or *technological*. While the first view attributes a robot's behaviors to higher purposes, framed as animate intentions and emotions, personality and volition, the second assigns causality to the inanimate material and informational building blocks which build up the mechanism of the system (i.e., physical parts such as motors and sensors, and the control program, governing the system's interactions). The two approaches are at times distinct, and in other cases entwined and related through growing experience with such artifacts. In this study, we search for and examine these two perspectives within the children's expressed ideas.

In our work with the young children, we challenged their reasoning with problems that involved understanding and constructing a robot's behaviors using rules. While we explored their spontaneous unmediated understanding, we've also supported their thinking through these problems. This support involved helping the children decompose the tasks, focusing their attention on pertinent environmental conditions and upon the robot's actions.

Background

What are the most essential traits at the core of the perception of a robot's 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; Braitenberg 1984; Scaife and van Duuren 1995; van Duuren and Scaife 1995; van Duuren and Scaife 1996); *function* versus *mechanism* (Piaget and Inhelder 1972; Miyake 1986; Granott 1991; Metz 1991; Mioduser et al. 1996); *function* versus *physical appearance* (Smith et al. 1996; Kemler-Nelson 1995; Diesendruck et al. 2003) and original (designer's) *intended function* versus *current function* (Bloom 1996; Matan and Carey 2001; Defeyter and German 2003).

Turkle (1984, p 45) reports on young children's conversations in naturalistic settings while they interact with smart toys, as centering on the meaning of what it is to be alive and act with intentionality**.** For example, five-year-old Lucy is sure that Speak and Spell (the game says words, which the child is asked to type in) is alive. Her older brother, eight-year-old Adam, disagrees with her: ''*OK, so it talks, but it's not really thinking of what it's saying. It's not alive.*'' In his view, intentionality is a condition for being alive**.** However, Lucy retorts back ''*You can't talk if you don't think, Adam. That's why babies can't talk. They don't know how to think good enough yet*.'' Confident of her judgment that talking beings are alive, she justifies her position with psychological principles**.**

The ambiguous status of computational objects among artifacts was demonstrated in a series of developmental studies (Scaife and van Duuren 1995; van Duuren and Scaife 1995; van Duuren and Scaife 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 objects have a brain. While children's ideas about the doll, the book and the person did not show any developmental differences, the ''clever artifacts'' -the robot and the computer- showed developmental differences**.** By the age of 7 years, children construe such intelligent machines as cognitive objects**.** They attribute them with a brain, but not a heart. Their written stories include several cognitive anthropomorphic references, attribute mental activity as well as volition to robots and computers, but not to other inanimate objects, such as bikes. Between the ages of five and seven years, children begin forming a differentiated concept of ''intelligent artifacts'', which can 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**.**

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.

Resnick and Martin (1991) describe these shifting perspectives in upper elementary-school students' perception of Lego robots as animals and as machines. They view this distinction as that among different levels of description: the psychological level, the mechanistic level and the information level (investigating how information flows from one part to another).

Against this background, the key over-arching question we have explored was: Do children use physical or psychological explanatory frameworks when reasoning about a behaving quasi-intelligent machine? To conduct this exploration, we used a *robotics environment* within which the children generated explanations and constructed a robot's adaptive behaviors.

The robotics environment

Vygotsky (1986) emphasizes the role of social interaction while learning. He describes children's learning of science as an upwards growth of spontaneous concepts towards greater generality, together with a downwards growth of instructed scientific concepts, which organize and help systematize the spontaneous concepts. The restructuring process occurs in social interaction and is mediated by sign systems. Vygotsky turns our attention to the ''Zone of Proximal Development''. In this zone, the child can participate in cultural practices slightly above his/her own individual capability. Successful participation can lead to internalization. Similarly, recent approaches of situated learning (Brown, Collins and Duguid 1989; Lave 1988) view learning as enculturation, the social construction of knowledge. They focus on learning in terms of relations between people, physical material and cultural communities (Lave and Wenger 1989). In the field of science education, Metz (2000) has shown that young elementary school children are able to grasp concepts and inquiry skills beyond those expected by developmental literature. She claims that these unexpected abilities are demonstrated when scaffolded by the following spheres of knowledge: (a) domain-specific knowledge; (b) knowledge of the enterprise of empirical inquiry; (c) domain-specific methodologies; (d) data representation, data analysis, and fundamental constructs of statistics and probability; and (e) relevant tools.

In this study, we explored the children's explanatory frameworks as these evolved within a multiple-partners environment, including the child, the adult/interviewer, and the robotic system. Differing from Metz's above supports for formal learning, 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 un-attended environmental conditions or robot actions, thus supporting their encoding of relevant task features (Siegler and Chen 1998). The children were not asked to use technological descriptions by the adult and were not taught how to use them. The other partner in the interaction space, the robot system, served the child as a concrete tool for the exploration and construction of abstract concepts and schemas.

Research questions

Aiming to unveil young students' perceptions of the functioning of adapting devices, our main research questions were:

1. *Through what perspective -psychological or technological- do young (five-six years old) children perceive an adaptive robot's behavior?*
2. *How does the children's perspective compare when their reasoning about the robots' behavior is spontaneous versus when an adult supports it by encouraging encoding of relevant task features?*

Method

Sample

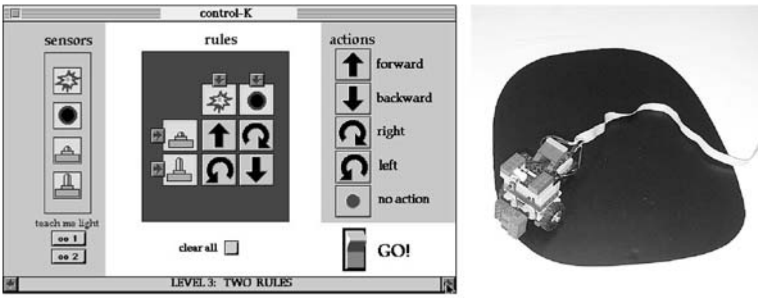
Six children participated in the study, three boys and three girls, selected randomly out of 60 children in an urban public school in the central area of Israel (socioeconomic status defined as mid-high). Their ages spanned from 5 years 6 months to 6 years 3 months, with a mean age of 5 years 9 months and a standard deviation of 3 months 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 this study. While we do use quantitative terms to describe the results, we place a reservation as to their validity.

Instruments

Two sets of instruments have been developed for the study: a computerized control environment and a sequence of tasks.

The computerized control environment was designed to scaffold the children's learning process. This environment includes a computer iconic-programming interface (Fig. 1a), a physical robot (made with Lego) and modifiable ''landscapes'' for the robot's navigation. The iconic interface allows the definition of the control rules in a simple and intuitive fashion (Talis et al. 1998). In the interface, the left panel shows the possible inputs—the information the sensors can collect and transmit; the right panel presents the possible actions the robot can perform; the ''programming board'' in the center is a matrix into



a b

Fig. 1 Iconic-programming interface (**a**) and ''guard of the island'' task setting (**b**) which the child drags the icons for inputs and outputs while constructing the control rules. For example, when the light sensor sees light and the touch sensor is pressed the robot moves forward.

The subjects in our study participated in a sequence braided of two strands of tasks: Description and Construction. In a Description task, the child portrays, narrates and explains a demonstrated robot behavior. In a Construction task, the child programs the robot's control rules to achieve a specific behavior. An example of a task is shown in Fig. 1b: The robot is placed upon an island; it moves across the island until reaching its edge; It then travels around the perimeter of the island, sniffing and following the island's rim. The tasks make use of the same robot in a variety of physical landscapes, and were designed as a progression of rule-base configurations, sequenced for increasing difficulty. The operational definition of *rule-base configuration* is the number of pairs of condition–action couples. The tasks spanned a range from half a rule (one condition–action couple), a complete rule (a pair of two related condition–action couples), two independent rules and two interrelated rules (made up of two pairs of condition–action couples). The full set of tasks is portrayed in Appendix 1.

Procedure

The study lasted five 30–45 min sessions, spaced about one week apart. The whole plan of the study is presented in Fig. 2. Each session focused on one stage in the rule-base configuration progression. Adult intervention was offered in the form of decomposing intervention, e.g., asking about conditions and actions, which are not noted in the child's explanation.

In this paper we focus on data collected for the children's *descriptions and explanations* of the robot behaviors. The children worked and were interviewed individually. The sessions were videotaped; the videotapes were transcribed; the transcriptions were segmented into 341 utterances. A content analysis was performed on these utterances, coding for the interviewer's interventions and the child's perspective.

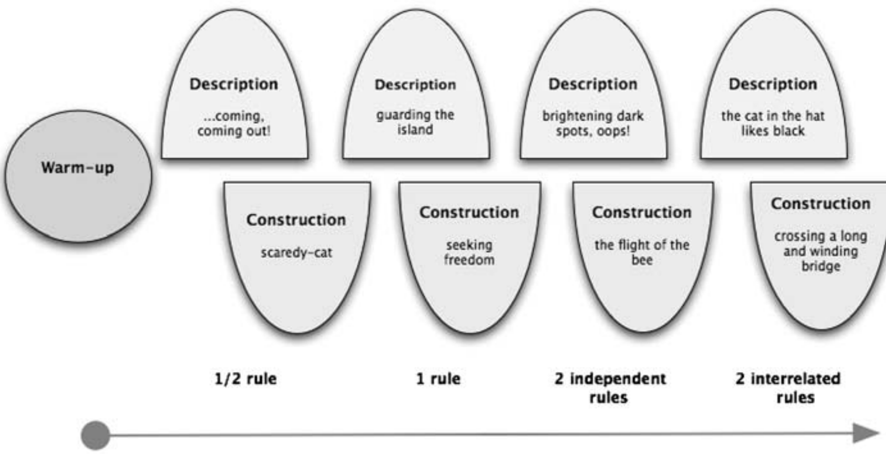


Fig. 2 Study design

In coding for interviewer's support, the children's responses were classified as ''spontaneous'' or ''supported'', according to the interviewer's questions. Responses to general questions and questions aimed at elaboration were coded as ''spontaneous'', i.e. presenting a general question (''What is happening here?''), and gentle probing for elaboration (''Can you tell me some more...''; ''What do you mean...''). ''Supported'' responses were provided to questions that focused on previously unmentioned specific conditions or actions in the system, e.g. ''What is the robot doing on the rug?'' ''Does it always turn?''.

The children's descriptions were coded as reflecting a psychological, technological or combined perspective.

The psychological perspective is seen in anthropomorphic descriptions, attributing intentions, mental states and affective causes to the robot. Examples of utterances classed under the *psychological perspective* are:

> *''He's searching for where there's more white paper.''*
> *''He's trying to pass between the barriers.''*
> *''He wants to be all the time on the blocks and he never wants to go on the white.''*

Descriptions referring to the building blocks of the robot functioning (e.g., motor functioning time or direction, sensor's input) were classed under the *technological perspective*. Examples of such utterances are:

> *''That the lamp ... always, when it's [the robot] on the white, then it [the lamp] tells him: no, it's not black, and when it gets to the black, it [the lamp] turns on.''*
> *''(Interviewer: How many things does it [the robot] do?) to sense... to listen to the computer... to do what the computer tells it to do... to blink [its lamp]... when it's on the flower.''*

We have also found expressions of *combined perspectives* such as the following:

> ''... and when he sees the rug he runs away from it. As if this [the rug] is the dark and the page is the light.''

In the first part of the utterance, the robot is attributed with intentions: running away from the rug. In the second part, a mapping is made between the rug and its property, which is sensed by the robot: the rug is ''the dark''.

Three independent coders (the authors and a graduate student) coded 20% of the transcripts. Inter-judge reliability was 93%. The remaining data were coded by the student and checked by the other judges to uncover obvious errors. An example of one such analysis is provided in Appendix 2.

Results

How do young children perceive an adaptive robot's behavior in terms of psychological and technological points of view?

The overall model devised in this study for framing our observations of the children's perceptions by the different perspectives, and of the mapping process between these, is presented in Figs. 3.

By this model, we refer to the various interrelationships (through the two perspectives) involved in the understanding and planning of adaptive behavior, e.g.: the relationship between inputs and outputs (in technological terms, or between contextual features and

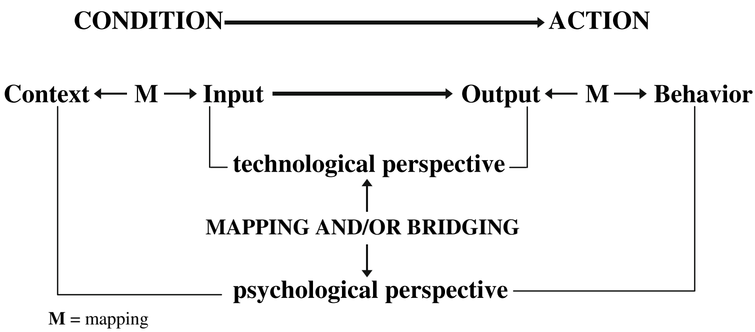


Fig. 3 Framework for the analysis of the rules in terms of psychological and technological perspectives, and the mapping (M) scheme among their components

behaviors (in psychological terms); mapping between contextual features and inputs, or between outputs and overall behaviors; or overall mapping—and at times bridging—between the psychological and technological perspectives.

In the following sections we present qualitative and quantitative accounts of the manifestation of the above perspectives in the children's spontaneous and supported explanations of the robot behaviors in the various tasks.

Qualitative observations

The following vignettes portray five salient themes concerning the children's perceptions: their technological descriptions; their psychological descriptions; how ''bridging'' descriptions map between the two perspectives; the children's view of the robot as an autonomous ''being''; and their view of its programmable nature.

Technological perspective

Examples of children's technological perspective can be found in their descriptions for the ''half-rule'' task. Here, the robot is enticed out of a cave by following a flashlight. One condition and one action suffice in defining the robot's control: ''if you see light, go forward''.

This task elicited mainly technological descriptions, such as Ron's. Throughout the sessions, he was fascinated by the interrelations between the mechanisms in the robot, its sensors and the computer program. Many times, he went off on his own exploration, inventing experiments and pinpointing several causal connections. He turned the robot about, touched its gears and wheels and went back and forth between the computer and the robot. In the following excerpt, he's observing the robot being drawn out of the cave with a flashlight:

Interviewer: Tell me what is happening.
Ron: *He* ***sensed*** *the light.*
Interviewer: What happened?
Ron: *He saw the light.*

Interviewer: Can you explain how this thing is working?
Ron: *With the* ***computer***.
Interviewer: How did the robot come out of the cave?
Ron: *We got him out of the cave with the flashlight.*

Ron references the technological components of the robot—its sensing capabilities as well as the computer program—involved in controlling its behavior. He has also extracted the particular feature in the environment, which causes the robot to come out of its cave: he speaks of ''light'' before he mentions the ''flashlight''. Even though Ron refers to the robot as ''he'' instead of ''it'', no other signs of animacy can be seen.

Psychological perspective

In the following weeks, a more difficult task was introduced: as ''guard of the island'', the robot is circling the rim of a white page on the background of a dark-green rug, with its ''nose'' on the edge (a light sensor for distinguishing between the white page and the dark rug). On the page, it goes forward, and when it reaches the rug, it turns. The children described the robot mainly through a psychological perspective, such as ''*he's searching for where there is more white paper*''.

The following exchange takes place with Naomi. Her main focus is on the intentional nature of the robot's behavior. She tends to use the words ''always'' ''never'' and ''all the time'' when talking about the robot, reflecting her constant search for invariance. In the following excerpt, she ignores the robot's actions and articulates its intentions.

Interviewer: What's happening here? What is it doing? How would you describe the behavior of this robot?
Naomi: *He all...* ***He doesn't know****, he doesn't know what this white is.*
Interviewer: And what is he doing? What does he know how to do?
Naomi: *He's all the time looking at him [the white ''island'' page]. He's all the time looking at this, and.. And he doesn't know what the white is; he's all the time looking at the white. He* ***doesn't want*** *to see the blue [rug]. He all the time wants to look at the white. He* ***doesn't understand*** *what is the white. He's all the time going around the white.*
Interviewer: Aha, he's going around the white. What happens when he gets to the rug?
Naomi: *He turns again...*
Interviewer: He's turning...
Naomi: *He's turning so he won't see the... [When summarizing, she says:] He's all the time looking at the white and he doesn't want to see the rug.*

Naomi focuses on the robot's knowledge state and related intention. It doesn't know what the white [island] is, that's why it spends all its time ''looking'' at it. He wants to learn about the ''white'' since he doesn't understand it. She articulates the reasons for the robot's actions, before describing these actions. The actions make up a small part of her narration. After focusing on the ''white'', the island upon which the robot is moving, she brings up another component: while the white paper interests the robot very much, he absolutely does *not* want to see the rug. This explains why he moves on the white paper and turns when it reaches the rug. She summarizes solely in terms of the robot's intentions.

Combined perspectives: shifting between explanations

A shift from a psychological to a technological perspective within a single explanation can be seen in the following description of the robot navigating upon a chessboard-like surface:

> ''He all the time wants to walk on the blocks [black squares] and he never wants to walk on the white. Only on the blocks, all the time. He's all the time on the blocks; and when he's on the white, he goes back to the blocks.''

The other way, a shift from a technological to a psychological perspective, is demonstrated in the following explanation by a child on a variation of the task, in which an additional input (a hat pressing a touch sensor) affects the robot's behavior:

> ''When there's something heavy on him, so he all the time turns and when there is nothing on him, so he doesn't turn at all. When there's something heavy on him, so he all the time turns so he can know where he's going. And when there's nothing on him, he goes wherever he wants''.

We want to elaborate further on how the two conceptual perspectives are related, following Mali's perspective shifts. In the first session, Mali observed and then programmed a robot, which has one light sensor facing upwards. She observed the robot coming out of a dark cave, following a flashlight. She programmed the robot with a complementing rule, to be ''afraid of the flashlight''. In the following week, she is observing the ''guard of the island''. Both tasks share the robot's sensor distinguishing among light and dark colors in the environment. This time, the light sensor is facing downwards. In the previous task, light and dark corresponded to ''*flashlight {implies} light*'' and ''*cave {implies} dark*''. However this time, light and dark correspond to the colors of the landscape, white [paper] and dark-green [rug]. Mali spends a while observing the robot circling the page.

Interviewer: What is it doing? Do you want to tell me what the robot is doing?
Mali: *He's walking all the time. And when he* ***reach****... [stops abruptly before ending the word] ...* ***sees*** *the rug he immediately runs away from him. As if this [the rug] is the dark and the page is the light.*

Mali starts with an intentional description ''*he... runs away*'' to explain the robot's overall behavior; it is fleeing the rug. However, within this portion of the description, she hesitates. She begins outlining the robot's flight from the rug as ''*when it reaches*'' the rug, stops mid-sentence, does not complete the word, and changes to ''*when he sees*''. This signifies a shift in focus from the robot's holistic location to its specific function of ''seeing''. While reaching the rug is framed in a psychological perspective ''being afraid of the rug'', the robot's seeing the rug is related to the robot's [technological] means of sensing its environment, seeing. Following this, Mali explicitly maps between the relevant environmental conditions, that are sensed through the robot's ''seeing'', comparing what she described through a psychological perspective with her description through a technological perspective: the rug is ''the dark'' and ''the page is the light''.

She is in fact using her experience in programming the robot, by abstracting from the contextualized concrete conditions in the previous task (shining flashlight, dark cave) to generalized abstracted features (light/dark), and then re-uses this abstraction in the new context (page/rug). Thus, the situated psychological-intentional description shifts, through reformulating the relevant robot actions, from *reaching* the critical location to the robot *sensing* that it reached this location. An explicit mapping occurred between these two forms: from psychological to technological conditions.

Perceiving a robot as both an intentional ''creature'' and as a computational object is at the heart of a mature cybernetic view (Ackermann 1991). Recognizing both its autonomous actions with respect to the environment and its programmability mark the bridge, which connects the two perspectives. The robot's reactivity to the environment, and its endowment with decision-making abilities, distinguish the robot as a psychological artifact. Its programmability sets it apart as a computational-technological artifact. We turn now to a closer examination of these two aspects of the children's perception of the robot: do they discern its *autonomy* as a prominent feature? How does *computation* play into their view of the robot?

An autonomous robot ''being''

van Duuren et al. (1998) have found that 5-year-old children did not use ideas of autonomy in distinguishing between robots who operated by rote (fixed sequences of actions) and adaptive robots. However, in their study, the children were not engaged in programming the robot. In our study, at the time the children participated in the tasks we report on in the following section, they have already programmed the robot twice: using a remote-control-like interface in the warm-up stage, and using the rules-definition interface in the single-rule stage for making a ''scared'' robot (it retreats from the flashlight).

In the following excerpt, Sarah is observing the robot in the ''guard of the island'' scenario. Sarah seems younger than the other children and she is very shy. She is slower in communicating and articulating her ideas. The interviewer interacts with her, gradually drawing her out. When she finally conveys a specific observation, she refers to the robot's autonomous movement.

Interviewer: I'm very interested to hear what you see the robot doing.
Sarah: *He's walking*.
Interviewer: How is it walking?
Sarah: *When you press the button*. [refers to running the program on the computer]
Interviewer: Is it just walking, or is it walking in a special way?
Sarah: *In a special way*.
Interviewer: And what's special about how it goes?
Sarah: *That he moves around* ***all by himself***.

Similarly, Ofer is singularly impressed by the robot's independence. Ofer has numerous questions, and many times answers an interviewer's question with one of his own. In the ''guarding the island'' scenario, the exchange starts out in the following way:

Interviewer: What is the robot doing?
Ofer: *How does he drive* ***all by himself?***

The robot's autonomy surprises and evokes Ofer's question, his prime and immediate reaction to its ability to drive along a self-determined route. Like Sarah, the most poignant aspect of the robot's behavior is its independence. Thus, it would seem that the children's construction of such systems, and especially construction of the robot's ''brains'', provokes their attention to this central distinguishing aspect of the robot's behavior—its autonomy.

The robot's programmability

According to van Duuren et al. (1998), 5-year-old children did not use ideas of programmability in describing adaptive robots. We expected the children in our study to form this connection, as a result of their growing experience in programming the robot. In the following excerpt, Ron is observing the robot (it navigates a surface splattered with dark spots or ''flowers'').

Interviewer: So that means... how many things does it [the robot] know to do?
Ron: *Lots.*
Interviewer: Tell me... I'm counting. One...
Ron: *To sense.*
Interviewer: The second thing he knows how to do...
Ron: *To listen.*
Interviewer: What? What does he know how to do?
Ron: *To listen to the computer.*
Interviewer: To listen to the computer? What is that, to listen to the computer?
Ron: *To do what the computer tells him.*
Interviewer: What the computer is telling it to do. What is this [the robot's lamp]?
Ron: *To flash its light.*
Interviewer: When does the computer tell it to flash its light?
Ron: *When it's on a flower.*

Ron is well aware that the robot is ''told what to do'' by the computer program; he focuses on the sensing mechanism, and the robot's programmability as the central aspects of the robot's behavior. The particular rules are subsidiary.

Thus, we can see that the connection between the robots' behaviors and the computer program is clarified through the activity of ''building brains'', or controlling the robot via the computer.

Table 1 Perspective taken in describing a robot's behavior in the different tasks without and with adult's decomposing intervention

	$^1/_2$ rule		Complete rule		2 independent rules		2 interrelated rules	
	spont.	supp.	spont.	supp.	spont.	supp.	spont.	supp.
S1	t	c	c	t	c	t	c	t
S2	c	t	p	c	c	t	c	t
S3	p	c	c	t	p	t	c	t
S4	t	t	p	t	t	t	p	t
S5	t	t	p	t	n/a	t	t	t
S6	/	/	/	/	t	t	t	t

t = technological description; p = psychological description; c = combined description

spont. = spontaneous description supp. = description supported by decomposing the task

(/ data missing due to technical difficulty in recording the interview)

Quantitative account of the observations: group patterns

In Table 1 we present data on the children's perspective in each task: their spontaneous descriptions, and those supported by the interviewer's probing questions helping the children encode the relevant features and decompose the task at hand.

Three children (S1, S2, S3) used combined descriptions, comprising both a psychological and technological perspective, from the very first task. They kept on using such combined descriptions throughout the tasks. For every task, they employed a combined description at least once. Three children (S4, S5, S6) never made use of combined descriptions. They offered relatively few psychological descriptions, and their explanations were mainly technological. Group level depiction of the data is presented in Table 2. A clear finding is that when supported in decomposing the task, the technological perspective is dominant.

Turning now to the results for the individual tasks, we will focus on the distribution among the three forms—psychological, technological and combined descriptions. In Fig. 4a, which portrays the children's spontaneous descriptions, we can see that in most tasks, the children started out with descriptions that included intentional or affective statements (67% of the spontaneous descriptions). In this, we include both psychological and combined descriptions.

In the first task, which was made up of one condition–action pair, few children offered a psychological description. Most of the descriptions were through a technological perspective. In the second task, which consisted of two condition–action pairs, we see no purely technological descriptions. In all cases, the children employed a psychological perspective, in some cases combined with a technological perspective.

Regarding our second research question, namely comparing the children's spontaneous and supported explanations, we found that with support (Fig. 4b), all the children generated technological descriptions. A large majority (86%) of the supported descriptions are through a purely technological perspective, and they completely monopolize the later tasks, as the combined descriptions are gradually eliminated.

Table 2 Perspectives (psychological, technological, combined) in the children's spontaneous and supported explanations. Results for the whole group, for the ''bridging'' subgroup and for the ''engineering'' subgroup

		All		'Bridging'		'Engineering'	
	Overall	spont.	supp.	spont.	supp.	spont.	supp.
Psychological	6 (14%)*	6 (27%)	0 (0%)	3 (25%)	0 (0%)	3 (30%)	0 (0%)
Technological	26 (59%)	7 (32%)	19 (86%)	1 (8%)	9 (75%)	6 (60%)	10 (100%)
Combined	11 (25%)	8 (36%)	3 (14%)	8 (67%)	3 (25%)	0 (0%)	0 (0%)
n/a	1 (2%)	1 (5%)				1 (10%)	
Total	44 (100%)	22 (100%)	22 (100%)	12 (100%)	12 (100%)	10 (100%)	10 (100%)

* N (%) = number of tasks for which an explanation was generated

spont. = spontaneous description supp. = description supported by decomposing the task

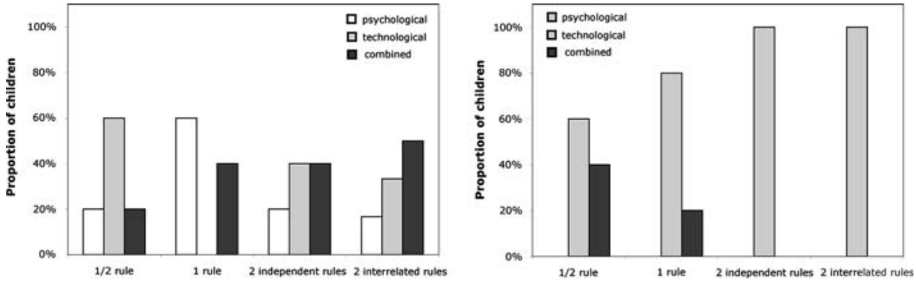


Fig. 4 Perspectives in describing the robot for each task – proportion of psychological, technological and combined descriptions for the children's spontaneous (**a**) and supported (**b**) explanations

Discussion

Perspectives in conceiving adapting robots' behaviors

In a previous paper (Mioduser et al. submitted), we explored and outlined how the children found repeating patterns from an erratic sequence of robot actions and abstracted these into rules. An initial haphazard sequence of robot actions (episode) was generalized to a repeating temporal pattern triggered by an environmental change (script), which was further abstracted to a set of rules, which relate the environmental conditions and the robot actions (rule). These gradually constructed knowledge representations, which we have described in the first article, capture the children's bottom-up interpretation of the robots' behaviors. Explanatory frameworks—the focus of this article—define the top-down perspective framing such reasoning.

What explanatory frameworks structure the children's thinking about behaving robots? Turkle (1984) and Ackermann (1991), as well as Braitenberg (1984), Hickling and Wellman (2001) and Scaife and van Duuren (1995) speak of two distinct explanatory frameworks with respect to the world of computational objects: the psychological and the technological. While the first view attributes the robot's behaviors to higher purposes, framed as animate intentions and emotions, personality and volition, the second assigns causality to the inanimate material and informational building blocks which build up the mechanism of the system (i.e., physical parts such as motors and sensors, and the control program, governing the system's interactions). The two approaches are at times distinct, and in other cases entwined and related through growing experience with such artifacts. In her proposal for a research framework, Ackermann (1991) claims that integrating the two kinds of explanations—synthesis of the behavioral and the psychological—are the core of a whole explanation. She argues that the ability to animate or give life to objects is a crucial step toward the construction of mature cybernetic theories.

In this study, we have examined these two perspectives within young kindergarten children's expressed ideas as they are engaged in observing and programming an autonomous robot and interact with an adult. With respect to our first research question, (namely, through what perspective the children perceive an adapting robot's behavior) we have found two distinct patterns: ''engineering'' and ''bridging''.

The ''engineering'' pattern shows a steady focus on the technical workings and the behavioral building blocks of the robot. The children tend to view the robot's behavior mainly through a technological perspective. In the following example, Ron is experimenting with a flashlight, shining it on the robot's sensor. ''*I want to see something... It's* *sensing also this... The point can move.... This way it doesn't sense. If you put it on this point, it senses... You can see the point.* [Interviewer: What happened there?] *He sensed the light... He moved to the back.*'' Ron is attempting to figure out how the sensor reacts to the light and concludes with a mechanistic description of the robot's response. In the ''engineering'' pattern, children tend to view the robots within a physical explanatory framework.

The ''bridging'' pattern consists of a combined psychological and technological perspective. In the following example we see Naomi shifting from an intentional description (the robot ''wants'' to walk on the blocks) to a mechanistic description (''goes... to the blocks''): ''*He all the time wants to walk on the blocks* [black squares] *and he never wants to walk on the white. Only on the blocks, all the time. He's all the time on the blocks; and when he's on the white, he goes back to the blocks.*'' The children employed two distinct perspectives in portraying the robot's behavior. More importantly, they coordinated between them.

We believe that these two patterns map onto Turkle and Papert's (1991) notions of ''hard'' and ''soft'' styles of programming. The ''hard'' style is described as a logical, systematic, analytical, hierarchical, abstract, distancing kind of relationship between the programmer and the program. The ''soft'' style is illustrated as a negotiating, concrete thinking and relational approach to the artifact at hand. While the ''engineering'' pattern we have observed in this study focuses on analyzing the technical workings of the machine, the ''bridging'' pattern can be conceived as a more negotiating approach, shifting between meanings and connecting the different forms of description. When ''bridging'', children are no less adept in forming a causal physical description. However, this is considered through a more relational framework. In anthropomorphizing the robot, the children bring it is closer to their own world, linking it to their understandings of themselves, as intentional and emotional beings, creating personal meanings with respect to the robot's curious actions. In Ackermann's (1991) terms, their approach can be construed as a more mature understanding of cybernetic artifacts, both separating and relating between the psychological and engineering aspects of the robot's operation. The engineering building blocks do not explain the higher objectives of putting them together in the first place. In giving meanings to the operation of such an object, one completes an understanding of the object acting with respect to its environment.

Additional points of interest can be seen as the children's perspective is analyzed by tasks. In the first scenario, the descriptions were mainly technological, e.g. ''*I just shine on him, and he continues straight*'' and ''*he's walking... when you press on the flashlight*''. In this setting, the children were asked about the behavior of a robot, where a single condition–action pair sufficed in providing an explanation. In a previous paper (Mioduser et al. submitted), we concluded that the children's spontaneous rules are capped at one condition–action pair. Therefore, this task was the only one which was within their capabilities to interpret the robot's behavior without the interviewer's intervention. In this case, the children did *not* usually exhibit anthropomorphic descriptions. Contrary to Ackermann's (1991) claim that young children tend to view cybernetic artifacts mainly in psychological terms, in the very first task the children in both groups were inclined to approach the robot exclusively in ''engineering'' terms.

Our interpretation of this contradistinction with Ackermann's claim is that anthropomorphizing can be seen as part of a bootstrapping process that aids in coping with difficult tasks. The psychological explanatory framework is more frequent when the task is beyond the level of difficulty which the child can interpret mechanistically, beyond one condition–action couple. From the second scenario on, when two condition–action pairs were necessary to formulate the technological building blocks of the robot's actions, the children's descriptions were predominantly psychological, e.g. ''*the robot wants to learn about the white*'' or ''*the robot runs away from the rug*''. Even the children who did *not* tend to describe the robot in psychological terms shifted into this perspective when the task was beyond their capability to interpret on their own. Why shift to a psychological perspective? The psychological perspective is more succinct. Technological descriptions are more detailed, complex, specific and locally attached to particular components of the system. A description in terms of a goal can summarize a complex of several rules in a single sweep: ''*it wants to go on the blocks*''. The rule structure of a psychological explanation is usually of one condition–action, describing an intention, state of mind or emotion. It is a larger ''chunk''. When a complex situation cannot be disentangled, it is advantageous to turn to the more terse form described through a psychological perspective. Thus, the children know the robot is a machine. They can explain its mechanics when the behaviors are simple enough. When the tasks require grasping a greater number of interacting components, the children turn to the simpler structure (and language and terms) of a psychological description.

When children combine perspectives, anthropomorphizing is also a continual means of sense-making, as it frames the *reasons* for the particular building blocks of the robot's behavior. Despite the fact that the technological components can be discerned and articulated, the children's explanations are couched within a frame of an animate object. How does a psychological explanatory framework aid in this process? A mobile robot, while clearly artificial with its blocks, wheels and sensors, does ''behave''. It does not perform a repeating sequence of actions, as does a washing machine filling up with water, adding soap and finally spinning dry. When it moves, varying friction in the terrain causes the robot to change direction in ways that are too complicated to predict. It reacts to local environmental features such as an irregularly curving line; it backs away from lights and barriers: its next step is usually difficult to anticipate. Regardless of this apparent randomness in sequence, the robot's behavior is clearly systematic with respect to a goal, such as seeking a line. In this case, the language for discussing artifacts and physical events is not useful in communicating what is sensible and regular in such a behavior. But in the psychological domain, such events are easily explained. Everyday psychology involves seeing oneself and others in terms of mental states—intentions, emotions, seeking goals, beliefs, knowledge states and internal decision-making are part-and-parcel of the essential perspective, as described by ''theory of mind'' (Wellman et al. 2001).

Purely psychological descriptions were most frequent in the second task, and then decreased in the succeeding tasks. We believe that the subsequent decrease reflects a general transition into the language of technology, as the children gradually appropriate the tools and language that come with constructing the robot's behavior. Even though the later tasks were more complex, we can see that the children are more focused on disentangling the technological complex of the robot's behavior. Support for this interpretation comes from additional aspects of the children's explanations. We have noted that some of the children refer directly to the robot's programmability. This is quite different from van Duuren et al's (1998) findings that younger 5-year-old children do not refer to this central quality of the robot. In their study, the children did not program the robots, but only observed their operation with a remote control and viewed movies of scenarios involving robots. Thus, we can see the deeper impact of the children's engagement with programming on their understanding of such ''clever'' computational objects.

Perceiving a robot as both an intentional ''creature'' and as computational object is at the heart of a mature cybernetic view (Ackermann 1991). Recognizing both its autonomous actions with respect to the environment and its programmability mark the bridge, which connects the two perspectives. The robot's reactivity to the environment, and its endowment with decision-making abilities, distinguish the robot as a psychological artifact. Its programmability sets it apart as a computational-technological artifact. While Poulin-Dubois et al. (1996) found that young infants discern self-propelled objects as anomalous, van Duuren et al (1998) have found that 5-year-old children did not use ideas of autonomy in distinguishing between robots that operated by rote (invariant sequences of actions) and adaptive robots. We have found that the children expressed surprise at the robot's autonomy and some saw this as its defining feature, fitting in with Poulin-Dubois et al's (1996) results. Thus, we can see that when involved in programming robots, rather than just observing or interacting with them, young children develop a more mature understanding of its cybernetic nature: its autonomy and programmability. In line with Metz's (2000) claim with regards to the crucial role of appropriate supports for young children's learning of advanced concepts and skills, in our study the robot system served the child as a concrete environment for the exploration and construction of abstract concepts and schemas. The robot is in fact a concrete system embodying abstract ideas and concepts, and a cyclical interplay is generated between this ''abstractions-embedded concrete-agent'', and the cognitive abstractions generated by the child about the ''abstractions-embedded concrete-agent''. This is the realm of thinking processes we referred to in a previous paper as the realm of ''concrete-abstractions'', in which recurring cycles intertwining the symbolic and the concrete are exercised by the child while abstracting schemas for understanding the robot's behavior (Mioduser et al. submitted).

An additional conclusion from this study is that the children do not use consistent explanatory frameworks. Children using predominantly an ''engineering'' or technological perspective used a psychological one when the task became too difficult for them to interpret. And children ''bridging'' between perspectives used mainly a technological perspective in the easier tasks. Thus, there is clear interaction between the task difficulty and the kinds of explanatory framework children reason through.

The impact of intervention on the children's perspectives

Regarding our second research question, namely comparing the children's spontaneous and supported explanations, we found that with intervention, almost in all cases, the children expressed a technological perspective regarding the robot's operation.

In the previous study (Mioduser et al. submitted), we have seen that the children tended to use rules more frequently when the interviewer intervened to help them attend to various aspects in the scenario under discussion. Moreover, they were able to use a greater number of rules than those they expressed spontaneously. The interviews had been planned to capture the children's spontaneous descriptions, but then provided support for the children's reasoning, by pulling their attention to unnoticed robot actions or relevant environment conditions. To summarize the results from both studies, such an interaction helped the children shift into *more complex technological rules*.

These findings reproduce results in similar studies, which examined how an adult's assistance in noticing and encoding relevant features in a situation is related to more intricate rule-base configurations (Siegler and Chen 1998). Viewing learning as enculturation, and knowledge as socially constructed (Vygotsky 1986; Brown et al. 1989; Lave 1988; Lave and Wenger 1989), we can see the children in this study growing through this interaction, stepping beyond their current abilities, appropriating a technological perspective in deciphering more complex rule sets than they could do on their own.

Implications for education

We have already suggested design principles in robot-programming learning environments, based on the learning progression we have found (Mioduser et al. submitted). We turn now to a more general question: Is it worthwhile to introduce such a challenging environment into early childhood classrooms?

This experiment did not take place in a classroom. The children interacted with an adult in an intimate tutoring relationship. Generalizing from this small sample and individualized ''laboratory'' setting to common classrooms is not trivial. However, we do believe that based on our results, it would be greatly worthwhile to invest in further research within classrooms. We have observed the children as they grew in their understanding of central concepts related to cybernetics: principles of feedback and control, emergent patterns that result from interactions between multiple rules underlying the robot's operation, its physical structure and its environment. On their own, the children were capable of deciphering the simpler robot's behavior. However, with further support their abilities were augmented. They appropriated the offered tools, thinking in ''concrete-abstractions'' about the robot's behavior and relating larger functional information to the intricate causal technological underpinnings. Furthermore, they could use these tools to construct desired robot behaviors.

Our research has highlighted also the primary role of an adult in promoting this higher-level thinking. We have offered successful interventions in this process helping the children notice the different robot actions and the related conditions in the environment. But the current study offers another point of view: the children approach the robot environment in different ways, using different perspectives and focusing on different aspects of the robots' behaviors. As in any diverse classroom, a teacher's role would be to notice the children's agendas and provide a motivating environment for all.

Finally, we have hopefully contributed to the research on young children's perception and learning of technological systems (Zuga 2004). Our particular focus on the adaptive behavior of controlled systems, complements and expands previous research on children's more general perception of technology (Jarvis and Rennie 1998) and their evolving design abilities (Fleer 1999, 2000; Carr 2000),

In light of the encouraging results of our exploratory studies, we believe that the interaction with knowledge-embedded artifacts in a supportive and playful classroom, represent clear opportunities for the children's intellectual growth and development.

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Appendix 1: Description and construction tasks

The tasks in this study are described in the following table in terms of their rule-base configuration, the overall robot behaviors, its environment, structure and underlying rules.

Appendix I Continued

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.

Appendix 1 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.

Appendix 2: Coded transcript

The following are transcripts of two conversations with Naomi, as she describes the robot ''Guarding an island'' and two weeks later as ''The cat in the hat likes black''. A full coding according to the variables is included.

Appendix 2 Continued

Transcription	Intervention	Perspective
Robot's behavior is demonstrated: the robot circles the rim of an island keeping its nose on the edge.		
I: What is he doing? How would you describe the behavior of this robot?	Spontaneous	Psychological
N: He's all... he doesn't know... he doesn't know what is this white.		
I: And what is it that he knows to do? What does he know how to do?	Spontaneous	Psychological
N: He's all the time looking at him [the white island].		
I: He's looking at the white [island] and what is he doing?	Supported	Technological
N: And what is he doing? He's all the time moving him... [the robot is moving the paper island a bit as it moves along it]		
N: He's all the time looking at it... And. He doesn't know what is the white. He's all the time looking at the white. He doesn't want to see the blue [rug]. He's all the time looking at the white. He doesn't understand what is the white.	Supported	Psychological
I: What does he do when he's looking at the white?	Supported	Technological
N: He's all the time turning on the white..		
I: He's turning on the white, and what happens when he gets to the rug?		
N: He turns again.		
I: He turns...	Spontaneous	Psychological
N: He turns so he won't see the ... [blue/rug]		
I: And he walks also in the middle of the white, in the middle of the page?	Supported	Technological
N: No. He walks all the time on the sides..		
I: Lets see what happens when I put him here like this. [Interviewer places robot in the middle of the page. The robot performs a different behavior from that observed so far - it goes straight till the edge of the paper. After this it replicates the earlier behavior]	Supported	Technological
N: And now it is going in a straight line. And then again to the left. And then again to the left. And again straight. And again straight he's going.		
I: Mmmm... N: All the time he's.. Now he's going backwards.		
I: Oh, this [part] fell off... You said that when he's on the white, what does he do?	Supported	Psychological
N: He's all the time looking at the white and he doesn't want to see the rug.		
[two weeks later]		
[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.]		
N: [looks at the robot] What did you do here? [looks at the computer]		

Appendix 2 continued

Transcription	Intervention	Perspective
I: ... Lets first look at the robot and try to understand what he's doing.	Light	Psychological
N: He wants to walk all the time wants to go on the blocks [black squares are blocks for N] And he never wants to walk on the white. He's on the blocks all the time		
...		
I: So you said, that without the hat he behaves differently on the white and on the black?	Heavy	Technological
N: Yes I: Yes? What does he do on the white?		
N: On the white he turns, and on the black he goes backwards and forwards.		
I: And when I put a hat on him he goes..		
N: Straight.		
I: And does it matter if it's black or white? N: No.		

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