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What pupils can learn from working with robotic direct manipulation environments

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Abstract This study investigates what pupils aged 10–12 can learn from working with robots, assuming that understanding robotics is a sign of technological literacy. We conducted cognitive and conceptual analysis to develop a frame of reference for determining pupils' understanding of robotics. Four perspectives were distinguished with increasing sophistication; "psychological", "technological", "function", and "controlled system". Using Lego® Mindstorms® NXT robots, as an example of a Direct Manipulation Environment, we developed and conducted a lesson plan to investigate pupils' reasoning patterns. There is ample evidence that pupils have little difficulty in understanding that robots are man-made technological and functional artifacts. Pupils' understanding of the controlled system concept, more specifically the complex sense-reason-act loop that is characteristic of robotics, can be fostered by means of problem solving tasks. The results are discussed with respect to pupils' developing technological literacy and the possibilities for teaching and learning in primary education.

Keywords Technological literacy · Robotics · Direct manipulation environments · Primary education · Technology education · Programming · Robotic concepts · Mind tools

Introduction

It is important for citizens to be technologically literate in order to participate in our highly knowledge intensive and technological society (de Vries 2006; Pearson and Young 2002; Rocard 2007). Several definitions of technological literacy circulate but all emphasize

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knowledge, ways of thinking and acting, and capabilities (Dugger and Gilberti 2007; Garmire and Pearson 2006; Jones and Moreland 2004; Moens 2008). In this study we focus on the contribution that working with robotic direct manipulation environments (such as Lego Mindstorms) in primary education may have on pupils' technological literacy. Robotics is widely considered to be one of the "big ideas" of present-day science and technology (Dijkgraaf et al. 2008; Hacker et al. 2009). Moreover, pupils will encounter robotics all their lives. Hence, robotics is relevant to primary education. To answer the question of what pupils (aged 10–12) learn from working with robotics, we developed a conceptual frame of reference based on the content of robotics itself and on the cognitive perspectives of learning in the domain of robotics. We used this framework to probe pupils' developing conceptual understanding and established a dialogical teaching context in which pupils explored robots and programs and solved robot design problems with Lego® Mindstorms® NXT, which functions as a dynamic modeling tool and as a Direct Manipulation Environment (DME) (Jonassen 2006; Slangen et al. 2009). From previous research we know that such an environment elicits intense discourse and thinking (Slangen et al. 2008). Our study is explorative in nature and yields insights into how pupils' conceptual development can be stimulated and enhanced by suitable tasks, discussions and teacher interventions.

Theoretical framework

The importance of robotics

In almost all sectors of society we encounter robotization, that is, automated systems. In industry, robots weld, transport, assemble and paint. In medicine, sophisticated robots help to conduct complex surgery. Robots mow grass and clean swimming pools. Robots milk cows and steer ships. Military robots make bombs safe, explore hostile areas, and kill people. The robot is one of the fifty "big ideas" in science and technology that should be known by everyone (Wisse 2008), even by pupils (Gifford 2005; Vanderborght 2008). Many science and technology educators advocate that such big ideas should receive more attention in the school curriculum (Kipperman 2009). Pupils themselves are well aware of the necessity of learning about robotics because of their likely ubiquitous presence in future society (Shin and Kim 2007). Economic, technological and social perspectives urge schools to prepare pupils for robotics (Verlaan et al. 2007). Automated systems should be an item in the primary school curriculum (Boeijen et al. 2010). This justifies precious time in school being devoted to robotics.

Becoming more technologically literate through robotic problems

Learning about science and technology and hence becoming *culturally* scientifically and technologically literate is not equivalent to becoming *functionally* scientific and technologically literate, in the sense of becoming a competent user or practitioner of science and technology (Hodson 1992; Jenkins 1990; van Eijck 2008). Functional technological literacy implies applicability and includes not only knowledge of technological concepts but also hands-on capabilities and acquaintance with the broader context of technology (Pearson and Young 2002). In order to attain this functional understanding of technology, it is important to use the design cycle in engineering (van Graft and Kemmers 2007). Walma van der Molen et al. (2009) suggest that an investigative approach, in which observations, models, hypotheses, predictions and experiments play a role, should be part of elementary science and technology education. Johnson (1997) suggests that conceptual technical knowledge can best be learned in situations that challenge the learner to analyze problems, develop solutions and learn from experiences. Furthermore, learning is greatly enhanced when pupils are exposed to social interactive environments in which language has an important role (Vygotsky 1986). Interaction with other learners and teachers stimulates reflection and helps build well-grounded and shared concepts. Although little research has been conducted into learning and teaching robotics in a primary school setting, noticeable work has focused on young pupils' understanding of robotics (Ackermann 1991, 2000; Levy and Mioduser 2008; Mioduser et al. 2009, 1996; Resnick and Martin 1991), stressing the importance of interaction with concrete materials.

We therefore suppose that robotics may best be learned by having pupils work in a context with realistic robotic problems including designing, constructing, programming, testing and optimizing, and not just by talking or reading. Moreover, we suppose that teachers have to scaffold pupils' learning by asking questions, providing feedback, pointing out inconsistencies, and elaborating on experiences and information, that is, dialogical teaching which stimulates and extends pupils' thinking and advances their learning and understanding (Alexander 2008). Recent insights reveal that important technological concepts, such as system thinking, design, and the form-function principle, have to be learned in a variety of relevant contexts so that generic insights can develop gradually (Hacker et al. 2009). We consider robotics to be such a context.

Robotic direct manipulation environments as learning context

We decided to make use of the Direct Manipulation Environment (DME) 'Lego® Mindstorms® NXT'. DMEs are mind tools (Jonassen 2006), educational materials that have the capacity to provoke discourse and higher-order thinking skills, such as analyzing, synthesizing, evaluating, and causal reasoning (Savage et al. 2003; Slangen et al. 2008, 2009; Sullivan 2008). Robotic DMEs provide a potentially rich context for learning scientific or technological knowledge (Hamner et al. 2008), for intuitive and formal understanding of concepts from physics, such as speed, acceleration, gravity, friction, force and balance (Krumholtz 1998), for understanding and practicing programming and engineering (Petre and Price 2004), for understanding concepts of robotics (Ackermann 1991, 2000; Levy and Mioduser 2008; Mioduser et al. 2009, 1996; Resnick and Martin 1991), and for developing general problem solving skills in the context of science and technology (Barak and Zadok 2009). Lego® Mindstorms® NXT robotics (Astolfo et al. 2007) consists of a programmable logic controller (PLC), sensors, actuators, icon based software, and constructive building materials which are relatively easy to work with. Even young pupils are able to work with such tools and arrive at an understanding of robots' emergent behavior (Mioduser et al. 2009).

A conceptual framework for robotics

To develop a frame of reference of what pupils can learn from robotics, a cognitive and content specific analysis is important. From a cognitive viewpoint, two perspectives have been proposed to explain young pupils' ideas. Young pupils show holistic conceptualizations of robots that can be regarded as psychological or technological, or a mixture of both (Ackermann 1991; Levy and Mioduser 2008). The psychological perspective refers to the pupils' idea that the behavior of a robot results from mental faculties similar to those of humans or animals. The technological perspective, on the other hand, conceptualizes the pupils' view of a robot as a constructed material entity, the result of human engineering.

Many pupils' first images and conceptions of robots come from experiences with toys, games, books, animations, and feature films. The *Gestalt* of the robot carries connotations of animated entities with human or animal-like properties. They move around, have arms, a head, eyes, and they do things by themselves. Hence, animistic or anthropomorphic characteristics such as volition, emotion, personality and intentionality force themselves on the mind of the beholder. Indeed, many people, including robotic experts, speak of robots in anthropomorphic terms. "Relating to artificial creatures as if they were partners enables people to experience/explore the dynamic of exchanges, the patterns of give and take, the degrees of mutual influence or control, so characteristics of human transactions" (Ackermann 2000).

For Levy and Mioduser (2008), who focus on young pupils of kindergarten age, this differentiation between two logically opposed conceptualizations suffices. In our study, we focus on older pupils, who may have more sophisticated ideas. Robots may still be black boxes to some of them, whereas others may have an understanding of what goes on under the hood. We therefore suggest deconstructing the technological perspective into more fundamental components through the means of a content specific analysis.

From a content specific approach, the term *robot* is usually applied to devices that work autonomously or by remote control, and especially to machines that perform specific tasks usually done by people (ter Horst et al. 2008; van Lith 2006; Vanderborght 2008). A robot is characterized by its *function*: it is a device that is meant to execute certain activities derived from problems, needs, or other challenges. A robot is unlike an animate being, which may perform the same function and activities, but whose abilities and actions (e.g., to see, to move, to act) cannot be reduced to a purpose originating from a functional problem analysis (Mioduser et al. 2009).

A robot is a *system*, that is, any group of interrelated parts designed collectively to achieve a designed goal. The system maintains its fundamental structure notwithstanding the possibility of infinite transformations. Systems have input, processes, and output. In order to perform a task a robot integrates solutions to sub-problems from different technological domains (e.g., mechanics, electronics, pneumatics, computing) into one machine.

The robot is a *construction* and as a rule consists of a frame with static components (bricks, pins, beams), dynamic mechanical components (gears, axles), electronic components (sensors, display, bulbs) and electro-mechanical components (motors). Robots should be well designed and constructed with the right components, and be stable and strong enough to enable the execution of the function(s). This requires understanding of concepts like stability, sturdiness, motion, et cetera. Though correct application of such concepts is necessary for a robot to function, they are not typical of robotics and can also be learned in other contexts. In this study, we will not focus on the concepts related to construction.

The robot is *controlled* by means of software designed to enable the robot to function. A robot reasons, in a way: it uses an algorithm to execute a task within the possibilities and limitations of the material construction. We distinguish between machines that run by means of an automatic mode and those that have interactive capacities. An automatic robot or automaton is based on an open loop principle (Barak and Zadok 2009; Hacker and Burghardt 2008). The activities of reasoning (R) and acting (A) are always executed in the same way and form an *R-A loop*. These devices incessantly repeat activities without taking into account external conditions. Only devices that have capabilities to interact (semi)autonomously, taking into account the (varying) conditions of the environment, are considered to be real robots. Such robots are based on closed feedback loops (Hacker and Burghardt 2008; Hacker et al. 2009) that are executed in varying ways depending on the input from the environment. Therefore, the performance of a robot is based on the three basic capabilities of sensing (S), reasoning (R) and acting(A), which repeat in succession and form the so-called *S-R-A loop* (van Lith 2006). A robot that is able to sense, reason and act needs hardware components like sensors, a PLC, and actuators (motors, bulbs, speakers, displays).

In this way, we have specified the technological perspective into more fundamental concepts. A robot is a functional controlled system, with the S-R-A loop as the most important defining characteristic. We elaborated this into four levels to describe pupil's ideas of robots: the psychological, technological, function, and controlled system perspective. Addressing this is pedagogically important in developing a more advanced and versatile conceptualization of robotics.

Psychological perspective: robots are animated creatures. Pupils attribute characteristics such as intention, consciousness, emotion, volition, or reflexes, or they mention limbs or organs implicitly referring to these attributes (e.g., the robot has eyes, which means 'he' knows 'his' position and recognizes the surroundings).

Technological perspective: robots are man-made devices able to act (move, walk, feel). They contain technical components (wires, chips, sensors, motors), are made of special matter (plastic, iron, rubber), and function according to technical processes (mechanical, programmed).

Function perspective: robots are man-made devices able to perform intended functions in order to solve a problem or to satisfy a need. This can be expressed in general (e.g., "work"), more specifically ("pick up things"), or in highly detailed terms ("replace a bolt").

Controlled system perspective: robots are man-made devices able to interact autonomously with the surroundings based on a pre-defined program or by means of remote control. Part of this perspective is the concept of the S-R-A loop.

Learning objectives

Being functionally technologically literate with respect to robotics implies that pupils are able to design, construct and program a robot that performs a function. This serves as the endpoint and criterion for successful learning. In line with the taxonomy of perspectives indicated above, pupils should gradually understand that:

1. Robots are artifacts, that is, they may appear to be animated but robotic behavior is based on technology (the technological perspective).
2. Robots are functional, that is, they are characterized and determined by their function, which is derived from some objective in real life (the function perspective).
3. Robots are systems, that is, each robot is a collection of separate components such as material parts and control software that have to be integrated into one entity in such a way that all these components are adapted to each other's function (the controlled systems perspective).
4. Robots are controlled systems, that is, a robot transforms sensory input into actions through a Sense-Reason-Act loop by means of a sequence of programmed instructions (the controlled systems perspective).

Research questions and methodology

In this study, we explore two questions. (1) What do pupils understand of robotics, that is, what perspectives and (key) concepts do they use to describe their knowledge, experiences and understanding of robotics? (2) How does the pupils' conceptual understanding of robotics develop, in the context of robotic problems that are offered through a DME? Zuga (2004) argues that the best way to identify such exploratory concepts is to use qualitative methods to observe students' learning.

Robotics is not a part of the standard curriculum in primary education in the Netherlands. Although some elementary school textbooks (ter Horst et al. 2008) include non-mandatory lessons on robotics, these predominantly have pupils reading, writing and talking about robotics in the context of paper and pencil instructions, focusing on knowledge about robots as the outcome. We therefore developed a new set of lessons on learning robotics that allows pupils to experience robots, provokes reflection and discourse, assists in the construction of relevant knowledge and insights, and develops their understanding through practice. This design should allow us to explore pupils' learning processes and conceptual learning outcomes in detail. We aimed to collect data on pupil's activities, discourse, reflections and achievements in this educational context. Derived from theory on one-to-one teaching experiments (Cobb and Steffe 1983), we designed a one-to-two teaching experiment: one teacher/researcher and two pupils. This allowed us to probe pupils' developing understanding better by analyzing their mutual interactions and those with the teacher: "in the course of an interaction, both the teacher and the pupils attempt to make sense of each other's verbal and nonverbal activity" (Cobb and Steffe 1983).

From literature and previous experiences with elementary school pupils, we had explicit and tacit expectations about what pupils may understand and may find difficult in the context of robotics. We elaborated this into the following set of questions and hypotheses that guided us through the research:

1. How do pupils conceptualize robots? We hypothesize that pupils know that robots are technological man-made artifacts and that they use both psychological and technical language to describe robots.
2. Are pupils able to develop a functional point of view? We hypothesize that pupils can come to understand that robots are defined by their function, but we do not know at which stage this occurs, or what triggers this development.
3. Do pupils perceive robots as integrated systems? We hypothesize that it would be difficult for pupils to consider systemic effects such as interactions between various parts.
4. Do pupils understand that robots are controlled by a program? We hypothesize that pupils know that robots contain a program written by humans. However, they may not know what a program really is.
5. Are pupils able to understand and apply the Sense-Reason-Act loop? We hypothesize that understanding the nature of the sensory input necessary for logical reasoning processes to decide upon actions, would be rather difficult for pupils.

The actual teaching experiment consisted of six 2-h lessons (Table 1) which were conducted during normal school hours but outside the classroom with pairs of pupils, age 11–12, in the last year of elementary education in an average school in an urban community in the south of the Netherlands. Six pairs, estimated to be the most talkative, were singled out for investigation. All pairs were followed through the first lessons. Three pairs were investigated during the whole trajectory.

The lessons were meant to draw the pupils' attention to the fundamental concepts of robotics as suggested by the questions and hypotheses above by confronting them with robotic phenomena, by urging them to investigate features, and by challenging them to design, build and program a robot that would fulfill a certain task.

Table 1 The lesson plan and research goals

Lesson	Goals	Activities
1	Part 1: Probe pupils' initial perspectives on robotics	Interactive discourse between teacher and two pupils about robotics
	Part 2: Probe pupils' initial understanding of the controlled system perspective	Analysis by the pupils of two apparently identical robots which, because of small mechanical, electronic or software differences, perform differently
2	Develop skills and understanding to work with the iconic program language, its components (blocks, parameters, variables, and values) and the relation with the actions of the robot	Attempts of the pupils to develop a simple program, such as making a robot run in a square
3	Develop understanding of an element of the controlled system perspective	Pupils analyze pre-made programs simple linear programs and more complex conditional programs; they predict the performance of the robot and explain differences between prediction and actual performance
4	Probe whether pupils are able to develop a controlled system and whether they base their thinking on conditional reasoning containing an S-R-A loop	Problem solving task (design, build, and program a robot that is able to detect a white sheet of paper on a black surface, stop on the white and raise a flag). Develop a list of demands, sketch the robot, write the initial program, and build the robot
5	Probe whether pupils' understanding of the functional perspective, the controlled system perspective and the S-R-A-loop is elaborated when pupils build and test robots	Testing the robot, focusing on deficiencies and optimizing the robot with respect to functional analysis, design, construction and program
6	Similar to lesson 5	Similar to lesson 5

In lesson one we explored the pupils' existing knowledge by talking about and examining various examples of robots. Furthermore, we drew pupils' awareness to the function and system aspects through the pupils comparing two outwardly identical robots which behaved differently. In the second and the third lesson the pupils explored the concept of control by studying the icon based program of a robot, by programming and testing simple R-A control programs, and by predicting the function and behavior of ready-made programs of different complexity. In the fourth lesson we presented pupils with a problem to solve: design, program and construct a robot that is able to find its way towards an "island" (white sheet of paper on a black floor of 4 m^2) without crashing into obstacles and then stop on the island and raise a flag. It aimed at the pupils' ability to analyze the problem context, formulate a program of demands, draw a simple but functional sketch of the robot and design the control program. The fifth lesson consisted of constructing the robot and testing the program developed in lesson four. Lesson six focused on further testing and optimizing the program.

The first author, who acted as a teacher, conducted the lessons. Through confronting the pupils with robots, through open questions and focused remarks, the pupils' attention was drawn to certain features and, in general, pupils were encouraged to speak and act. The teacher tried to stay within the zone of proximal development of the pupils (Vygotsky 1986), creating some constructive friction but never forcing them to do things they apparently did not yet understand. Each lesson was recorded, with one camera focusing on the pupils, their mutual interactions, the construction and testing activities and the conversations with the researcher. A webcam recorded the pupil's programming, while screen captures were continuously made with Camtasia 5.

To make sense of the emerging data we followed the principles of grounded theory (Strauss and Corbin 1990). This methodology is suitable for analyzing and explaining discourse and actions of participants. Verbalizations and actions were coded by the first author with the aid of Atlas.ti, using the four perspectives (psychological, technological, functional and controlled system) as labels. The reliability of coding was tested against the second author and revised until full agreement occurred. Qualitative analysis of the conversations and robotic DME activities was performed to compare pupils' conceptual understanding of robots in more detail with the hypotheses. We explored pupils' understanding with respect to function, system, control, and the sense-reason-act loop. We looked for indications that DME activities contribute to conceptual development. Conversations that appeared to reveal insights into pupils' understanding were transcribed in full and discussed in the research team. Emerging interpretations on pupils' concepts and conceptual development, including our own tacit intuitions and hypotheses that gradually became more explicit, were tested and retested for robustness and representativeness against the whole dataset.

Results

In this section, we present the data that reveal the perspectives pupils use in interacting with robots, how they apply their understanding in practice, and how their understanding develops through reflection and discussion.

Perspectives pupils use

In the first lesson our intention was to unravel which perspectives pupils use or do not use. The researcher started an open dialogue to explore pupils' conceptualization of robots, showing and manipulating some robots, mainly from toy shops. He asked questions like: "What are these?", "What are robots?", "What are they made of?", "Are all these things robots?", "Do you know other kind of robots?", "What makes robots different or similar with respect to animals or humans?", "Why do people build robots?" et cetera. When possible, the researcher confronted the pupils with puzzling aspects in their descriptions and definitions. It turned out to be relatively straightforward to label chunks of discourse and activities in the first lesson using the four perspectives. The results are shown in Table 2.

Not unexpectedly, the pupils predominantly used descriptions and words referring to the psychological, technological, and function perspective, but the more advanced control system perspective also emerged. Pupils know that robots have functions rather than intentions, and that they are developed to do activities according to a set purpose. On a few occasions pupils showed an understanding of robots as controlled interactive technical systems. We probed the psychological perspective, since pupils regularly use words and phrases consistent with this perspective: robots "can see", can "be afraid", "can walk" et cetera:

> Pupil 2: They also made a soccer player robot but it kicked slantwise. They are now working on it [so] that he thinks as a real human.

Table 2 Prevalence of perspectives in the first lesson

	Psychological perspective		Technological perspective		Function perspective		Controlled system perspective		Total
	n	%	*n*	%	*n*	%	*n*	%	
Gr 1	11	33.3	8	24.2	11	33.3	3	9.1	33
Gr 2	0	0.0	12	41.4	12	41.4	5	17.2	29
Gr 3	10	47.6	8	38.1	1	4.8	2	9.5	21
Gr 4	3	13.6	7	31.8	8	36.4	4	18.2	22
Gr 5	4	15.4	7	26.9	9	34.6	6	23.1	26
Gr 6	5	25.0	8	40.0	4	20.0	3	15.0	20
Total	33	22.5	50	33.7	45	28.4	23	15.4	151

Researcher: Why does the robot stop close to the object? Pupil 4: He saw that.

Pupil 1: If he [a scorpion-like robot] thinks he will be attacked then he starts doing that [hitting]. Pupil 2: When he touches something then he goes backwards. If he feels attacked he will sting like a real scorpion.

Pupils said "the robot looks" instead of "the sensor detects", "the robot thinks" instead of "the program compares". However, when pupils focused on the constructive and material features, their descriptions became much less animated and clearly revealed the technological perspective, in which a robot is a man-made device made of metal, wires, sensors, et cetera and can "move", "see", "grasp", but not in a human way.

Researcher: Why does the robot move backwards? Pupil 6: He sees us with the sensor. Pupil 5: He sees us with his eyes. Pupil 6: No, these are feeling sensors.

Researcher: What are robots made of? Pupil 3: Steel, plastics, wires, copper wire. Researcher: What more? Pupil 3: Printed circuit boards.

Pupil 2: This is the sound sensor. Researcher: What is a sound sensor? Pupil 2: I think when he hears that he is too close to something that the program perceives this and that the robot then starts making a noise.

The above extract is characteristic of dialogues with most pupils. We conclude that these pupils know that robots are programmed artificial constructions, although they regularly use humanoid characterizations and descriptions. In this, they do not differ much from mature engineers.

The function perspective

It proved to be rather difficult to focus pupils' attention on functionality in the sense of conducting a specific task or solving a specific problem through appropriate behavior of the robot. Pupils defined functionality in more generic terms, e.g., robots are for playing, for simulating humans, or for making life easier, and sometimes focused on the quality of materials or near-to-human abilities. The following quotes also come from the first lesson:

Researcher: Why do people build robots? Pupil 7: They make robots for competitions. Researcher: Do you know more? Pupil 8: Toys for pupils.

> Researcher: Why do people make robots? Pupil 11: In order to make it easier. Researcher: To make what easier? Pupil 12: Also to speed things up.

> Researcher: What makes a robot a good robot? Pupil 6: It must be able to talk…. Pupil 5: Good materials, so that it can move, something like rubber so that the legs can turn into all directions like humans… and have a nice skin.

More pointed questions on the purpose of robots were needed to elicit more specific answers from pupils. “To work in factories” is still rather generic, “picking things up” becomes somewhat more specific. However, such answers are rare in this initial stage:

> Researcher: What are robots made for? Pupil 1: To work in factories, pick things up from the conveyor belt and put it on another one.

Only a few pupils explicitly related a robot’s apparent autonomy to successful execution of a dedicated function. Even then, their phrasing was very general:

> Researcher: What is most important [feature] of a robot? Pupil 1: Yes that it can do something, that it is useful for something. Pupil 2: That is does what is assigned.

> Researcher: What are good robots? Pupil 11: Robots who do things that you would like them to do.

> Researcher: What are robots, according to you? Pupil 9: Devices that can do things on their own. Pupil 10: By means of the stuff that is in it.

In this conceptualization, robots retained many elements of a black box. Robots do things, but, without knowing what goes on under the hood, one remains a passive spectator and recipient.

We anticipated that talking with pupils about robots in a context without a problem to be solved or a task to be executed is not the most effective way to elaborate pupils’ concept of functionality as a key concept in understanding robotic systems. The next lessons had pupils solving problems. These indeed led to clearer conceptions of the function perspective. While designing, constructing, programming and testing the robot, the pupils focused on the relation between form (design) and function and became aware that achievement of a function depends on well-functioning parts.

> Researcher: Do you still know what the purpose of your robot is? Pupil 5: Yes, he must locate the island on the black floor. Pupil 5: Yes. Researcher: Here is an island [white sheet of paper] and a black floor. Pupil 5: And when he locates the island a flag has to fly on top.

> Researcher: And how would the robot find the white island? Pupils 1 and 2: With the light sensor. Researcher: And how did you discover that there is a light sensor? Pupil 2: We thought about a light sensor, which would be able to search the floor for bright colors, because the floor here is brown. Pupil 1: And white is bright. Pupil 2: And you can see the bright white paper. But for a robot it is different. The robot should search for it because the robot cannot look. He must do as he is instructed.

We conjecture that developing pupils’ understanding of the function perspective implies redirecting their attention from generic classes of robotic purposes (to play with, to simulate humans, to make life easier, to conduct dangerous work, etc.) to more specific situations. By focusing on embedded problems and design tasks functionality emerges from the necessity to design forms that achieve a specific goal.

The system perspective

In the next step, we probed pupils' (developing) understanding of the system perspective. Do they understand the consequences of the fact that a robot integrates all functional elements in one device? Successful robot development implies consciously taking into account the mutual interactions between all the constructive and virtual elements during the design, construction, and testing phases, that is, approaching the robot as a system that consists of subsystems, parts and processes. Pupils are not experienced robot developers and we expected that, at the outset, they would not yet be aware of the coherence and interactions of all these elements, and that they, as designers, may have influence on this system.

To most pupils a robot initially was what it does:

> Researcher: Do you still know what he had to be able to? Pupil 4: Yes bring up the flag, driving.

> Researcher: How to drive? Pupil 4: Straight forward, backwards, left, right. Pupil 3: To see, to feel.

Seeing, feeling, and driving are characteristics of the whole robot but are brought about by different subsystems. By having pupils compare robots that appear similar but behave differently, and giving the pupils the task to make the robots act identically, we drew pupils' attention to these various subsystems and their specific contribution to achievement. Three kinds of bugs (a gear that was not attached, a cable plugged in wrongly, a software bug) resulted in the same symptom (one wheel did not turn). A well-functioning version of the same robot was present to enable comparison. From previous research, we already knew that pupils of this age possess the necessary analyzing, reasoning and evaluation skills (Slangen et al. 2008) for such a task. This analytic approach seemed to work well, since all pairs detected and repaired the bugs. In this problem solving context, pupils successfully identified subsystems or parts and their proper function. They posed and tested hypotheses about relationships between parts and used more precise language than before:

> Researcher: How did you discover what exactly the sensor is? Pupil 1: That [points at the well-functioning robot] was just doing fine. And if you disconnect that one thing [wire and sensor] and then let him drive to look if it is still working. And then if it did work it was not the sensor. Researcher: By disconnecting the wire you discovered that it was the sensor that was responsible for stopping. Pupil 1: [connects the wire again] When we let him drive again it should work again. [performs this test] Pupil 1: Yes, it works again.

In the last three lessons, we operated the other way round and asked pupils to develop a robot from scratch that was able to perform a pre-defined task in a given context, 'The island task' (Fig. 1).

To solve this problem, pupils analyzed the task and context, developed a list of demands and functions, drew sketches, and constructed, programmed and tested the robot. While going through these stages, pupils must anticipate the consequences of their choices with regard to the whole system, subsystems, parts, processes and their interactions. This helped most of them to recognize that parts and systems, especially constructive elements, the control system, and the S-R-A loop have to be adapted to each other:

Fig. 1 The island task

> Pupil 7: Maybe the light sensor should be between the wheels? Researcher: Why? Pupil 7: Because now it is in the front. Researcher: Why is that a disadvantage? Pupil 8: In this way it stops too early. He stops when he sees [the island]. Pupil 7: But he has not yet arrived on the island.

> [Pupils are programming the raising of the flag with a "move" icon in the program] Researcher: How can I ensure that the correct motor is chosen? Pupil 5: Here, port A, B or C. Researcher: What is it? Pupil 6: Yes, one motor is connected to port A. Pupil 5: Because the real motors [points at the wheels] are connected to B and C.

> [Analyzing a bug in the program] Pupil 6: Try this part first until it functions well, and then include the next part, and if that functions you include the last part.

Although still largely implicit, system thinking seems to emerge in these dialogues. The ability to "see" properly is no longer attributed to the robot as such, but is related to the position of a sensor in the whole construction. Different parts of the program become related. The flag does not raise itself; this is the result of properly programmed instructions and correct connections to the output port. Discourse on construction or program helps pupils to reflect on the coherence between separated systems, subsystems and parts. However, these signs of system thinking appeared infrequently and not with all pupils. It was not yet a conscious approach to robotic problems for all pupils.

The controlled system perspective

People tend to use categories like emotion, feeling and intelligence to describe the behavior of simple, autonomously operating vehicles (Braitenberg 1984). In line with this, we expect that pupils will not articulate their knowledge of programs spontaneously but use terms like "think", "know", "feel", or "want" instead. This may hinder pupils from developing an accurate understanding of how to control robots through programming, which is a necessary and essential part of a functional understanding of robotics. In the second and third lessons we wanted to probe pupils' way of speaking about robotic control and develop their understanding by explicitly drawing their attention to the program as the tool to achieve its function.

We used the Lego Mindstorms programming language (Fig. 2), which consists of iconic objects, named "blocks", representing an instruction or a combination of instructions (e.g., "act on motor 1", or "use input from sensor B"). These blocks are easily manipulated by using "drag and drop" techniques. Every block has an appropriate set of parameters with adjustable values (e.g., "turn left wheel 15 rotations"). A program is a sequence of

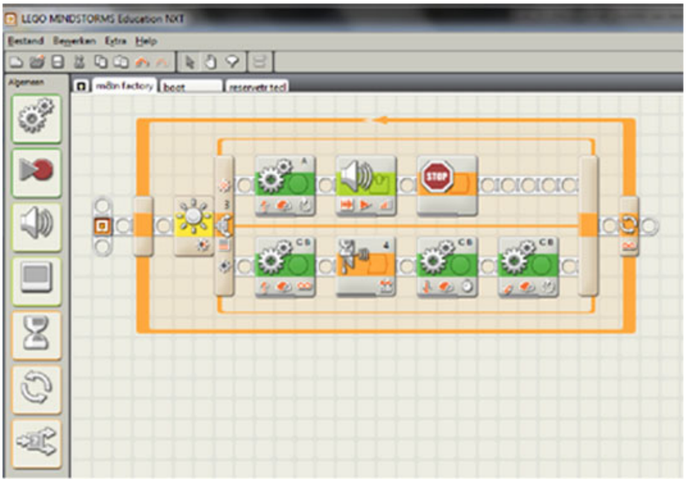

Fig. 2 An example of a Lego® Mindstorms® NXT program to find the island and raise the flag

software instructions (blocks) that determines the internal and external state of the robot, performs calculations using this input, and initiates actions by commanding the actuators, thus changing the internal and external state. From accounts of use of Lego Mindstorms worldwide and our own previous experience, we conjectured that most pupils in the age group studied would be able to pick up the syntax and semantics of this language, although we did not yet know with what fluency and flexibility.

Our observations confirmed that pupils initially do not explicitly refer to the existence of an innate intermediate logical reasoning facility for mediating between sensing and acting and controlling robotic behavior. They connected sensing directly to acting to explain their observations:

> Pupil 4: He [a toy insect robot] walked just like that and then it felt with the antennas that it had to move backwards.

As expected, it was not difficult to let pupils explicate their tacit knowledge on the existence and importance of an internal reasoning process:

> Researcher: Why do the robots act differently? Is it because of their names [robot dog 1 & robot dog 2]? Pupil 1: It can be that you put something different in this one. Pupil 2: Yes, differently programmed.

> Researcher: What are programs? Pupil 1: How he walks and talks, and the sounds he makes, you can change all of that, when you wish you can also delete that.

From this, it was easy to challenge pupils to improve the program themselves. For this purpose, we confronted them with some short programs with increasing difficulty on the computer screen. We asked the pupils to analyze and predict the robot's behavior and subsequently test that prediction. As expected, most pupils quickly became familiar with the programming language, saw differences and similarities between the programs, and were able to adjust, improve and elaborate:

> [The robot has to ride a square. However, the corners are larger than 90 degrees. The parameter setting is 0.5 s] Pupil 3: Rotation time is 0.5, maybe we can …. I am going

to try if it succeeds with 4. Pupil 4: I try 0.6? Pupil 3: Wait a moment. Researcher: 4? Pupil 3: 0.4. Pupil 4: He is now riding lopsided. He is still increasingly lopsided. It must be bigger than 0.6.

When pupils recognized that robots can do different things as a result of the internal program, this challenged them to explore the meaning of the icons, parameters and values of the program. It appears to us that pupils did not require much explanation to recognize the relation between preferred output and programmed instructions. They developed an insight that actions depend on parameters and values specified in the program.

Pupil 3: Here we have to click how long he moves. Pupil 4: "Control C", what does that mean? Pupil 3: Length of duration is 1, do we have to give him longer? Pupil 4: One-second. Pupil 3: And power must also be more. Pupil 4: Rotation. Pupil 3: Next action is here. Pupil 3: Degrees unlimited.

Pupils clearly saw that they can program actions. However, there are two ways to control devices: in an open loop program that specifies actions but does not take into account input from outside (the "reason-act loop") and in a closed loop program that does take into account external input (the "sense-reason-act loop").

When stimulated to program a robot that runs in a square, most pupils programmed an R-A sequence of about eight chunks which controlled motor actions with "move" blocks. These blocks successively executed the instructions to move forward, to turn, to move forward, to turn, et cetera.

Researcher: The first block makes the robot turn, what does the second block do? Pupil 9: Lets him move too … Researcher: The second block makes him? Pupil 10: Move straight forward, and the third block must make him turn again. Researcher: The fourth block? Pupil 9: Wait, we are not there yet, these have to be correct first. Pupil 10: This one has to go to the right. Pupil 9: No, the other side. Researcher: Why the other side? Pupil 9: Because this one is already there. The next one has to move straight forward.

In their first lessons, pupils predominantly created R-A programs using "move" blocks only. With some help pupils discovered iterations with fixed values to shorten or to make well-arranged programs.

Researcher: He has turned only half a circle and how many times does he have to turn? Pupil 7: Two. Pupil 8: You must use the iteration and then set it at two. Pupil 7: Or do we set it at 200, then he turns a hundred squares?

Initially, for pupils, the differences between an automaton (R-A loop) and a robot (S-R-A loop) were diffuse. However, they soon started exploring the "sensor blocks" in order to let the robot stop in front of an object. This means that the pupils understood that this is to be achieved using external input. At this stage, correct reasoning with external input seems to be too difficult for most pupils. As we see in the next quote, one child was still reasoning with fixed parameter values, while the other already focused on external conditional input.

Researcher: Why does the robot stop now? Pupil 3: Because it is [value of the parameter "time"] 15 s. That is how long he has to run. And then this ultrasonic block and the halt sign have absolutely nothing to do with that because it stops after 15 s. Pupil 4: Then we must increase it [parameter time]. Researcher: Look for other solutions. Pupil 3: No, we have to change this [parameter time] to "unlimited".

> Researcher: What is "unlimited"? Pupil 3: That it goes on running and then the ultrasonic says "stop now". Otherwise you run against the wall. Pupil 4: Oh yes.

We notice that reasoning with external input seems to be within pupils' zone of proximal development but successful application is still difficult. Instead of applying sensors, pupils tried to circumvent this more complicated conditional reasoning as long as possible.

> Researcher: Does the robot stop with the sensor? Pupil 3: I removed the sensor.

> [The pupils try to use a sensor block but without the desired effect] Pupil 8: Maybe we have to know how many seconds it takes. Pupil 7: I think it is not more than 60 s. Pupil 8: Otherwise you have to count. Pupil 7: But it also depends on the distance from the starting position.

> Pupil 4: We must change the starting position. [Pupil 3: moves the robot closer to the island].

We conclude that pupils initially approach robotic activity in a holistic way, as if the robotic program is akin to some kind of cognition. They have no idea what the program looks like and how it works. However, by acquainting pupils with the programming language (blocks, parameters and values) they are enabled to develop simple Reason-Act control programs. The availability of sensors as a constructive possibility and in the programming language triggers its use. Educationally, this process of trial, error and reflection prepares pupils for a subsequent step: solving problems with conditional reasoning.

The sense-reason-act loop

The heart of robotics is the repeated interactive sequence of sensing the present condition, comparing the resulting information algorithmically in the Programmable Logic Controller to a condition that represents task fulfillment, and generating output information that drives actuators to actions meant to equal these two conditions. "In studying robotics, students learn about the parts of the system, the functional relations between the computer program and the output devices (motors and tower), and the causal interaction between the computer program, the input devices (sensors), and the output devices (motors)" (Sullivan 2008). We wanted to explore whether pupils are able to develop the S-R-A concept, knowing now that they possess a functional R-A concept, and which experiences and interventions stimulate this development. The S-R-A concept requires the understanding that the program should continuously compare the external condition with the desired condition. Actions then become conditional and not automatic. This requires logical reasoning of the "if … then …", "wait … until…", "repeat … until…" kind.

We presented pupils with devices that continued their action ("moving around") perpetually but halted when a certain occasion presented itself (e.g., when the robot is within 20 cm of an object). Several pupils understood that sensory input and a program are responsible for halting:

> Researcher: What does this robot do? Pupil 4: In some way he can see. Pupil 3: He stops when this is in between. Researcher: Between what? Pupil 4: He is running squares and when you, for example, at some point you put a paper sheet in front of the robot it stops.

When pupils' attention was focused on how sensors may cause halting or changing actions, they were able to grasp the meaning of items in existing programs:

> Pupil 4: Do you think this robot will stop? Pupil 3: No, there is no ultrasonic block in the program. Researcher: What is the ultrasonic block for? Both pupils: The ultrasonic block makes the robot stop.

> Researcher: If that ultrasonic sensor detects a wall at 20 cm, what happens? Pupil 4: It stops, it should stop. Researcher: It should stop but does it stop? Pupil 4: No. Pupil 3: Here is a stop block. Researcher: All right, put it in the program and let us see what happens.

Programming a sense-reason-act loop implies that the robot should continue its action endlessly (e.g., moving around, waiting, making noise) until sensory input and conditional reasoning changes or stops the action. This is markedly different from the reason-act loop approach, in which pupils attempted to program static and sequential actions. We observed that several pupils were able to adopt this new approach.

> Pupil 3: He runs first. Pupil 4: He follows the blocks. Researcher: What does he do in the blocks? Pupil 4: He follows them. Pupil 3: He is doing the same all the time [iteration] until something is in front of the robot and then he arrives in a different block [iteration] and then he runs [for] 3 s. Pupil 4: Backwards. Pupil 3: And then everything starts again. Then he will drive again until an object is detected, then he runs backwards [for] 3 s.

Understanding the S-R-A loop implies that pupils who use a sensor to allow the robot to look, hear, or feel ("sense") explicitly understand the relation between an initial process that compares internal values with the values of the external situation and decides which path to follow ("reason") and a subsequent process that tells the robot how to react ("act"). This understanding in principle empowers pupils to develop a robot that actually solves problems. However, success also requires flawless programming, a good choice of sensors and actuators and a good system thinking with regard to design and construction. Most pupils grasped the general idea of the sense-reason-act concept but the vast set of instructions, parameters, operators and syntax rules confused them easily and was a potential source of mistakes. Synchronous execution and interaction of two or more actions appeared to be difficult. For example, how to program a robot that should continuously sense the distance of objects while driving around and simultaneously sense the light intensity? We noticed that most pupils fall back to R-A loop thinking. They replace the complex conditional reasoning on the basis of sensory input ("if … then …") with unconditional sequencing of actions (first do this, then do that, do it for 10 s et cetera). They lack fluency with the more complicated language of conditional reasoning and nesting necessary for successful programming and they had to be helped considerably with this.

> Researcher: He stops if the distance is more than 30 cm? Pupil 4: That is it, I think. Pupil 3: No, then he always stops. No, we have to put him at "less than".

Another complication arises in this respect. Some understanding of the physical principles that rule sensors is helpful when someone uses sensors. This requires substantial knowledge of the device (Mioduser et al. 1996). Sensing is not "seeing" the way humans see, but can be measuring a distance with an ultrasonic sensor, or measuring changes in the intensity of reflections with an infrared sensor, et cetera. Pupils are not used to approaching the natural environment in this way. They have striking but completely understandable difficulties in translating the human concept of searching into adequate robotic language. For instance, an engineer might say: “Move around continuously and make a random turn when the ultrasonic sensor spots a blocking object. Meanwhile, continuously scan the floor with the light sensor. When the intensity of the reflected light is high, stop. Otherwise, keep moving around.” Pupils grope for this language with conjectures like: “If the sensor sees the white color, he knows he is there”. This reveals that there is some way to go from opening the black box of robotics to obtaining fluency in problem solving with sense-reason-act loops.

Summary of results

We conjectured that pupils know that robots are man-made artifacts and not living beings, even when they use psychological terms to describe or explain a robot’s material characteristics and functions. Data analysis revealed that pupils’ initial concept of a robot indeed contains such elements, but that they also know that robots are man-made technical products. They use the technological perspective to describe robots, although they have difficulties finding the appropriate words. In their explanations, pupils use words that normally apply to human activity: “a robot looks” instead of “a sensor detects”, “the robot thinks” instead of “the program compares”. Their speech changes gradually to a more technically precise language under the influence of problem solving and design activities, the corresponding experiences and the scaffolding dialogues with the teacher. This implies a shift from mere cultural literacy towards a more functional literacy.

We conjectured that pupils can understand that robots are defined by their function. Initially, signs of a function perspective are weak and phrased in rather generic language. We have indications that conceptual change towards more precision is attained through three levels. In the first level pupils refer to general classes of robotic purposes (to play with, to simulate humans, to make life easier, to conduct dangerous work etc.). Next, they refer to contextual relations and actions (work in a factory to pick up things from a conveyor belt). Third, they refer to a robot’s apparent autonomy and interactivity as related to execution of a dedicated function. Pupils attained this level of functionality by means of a problem solving task that included design, construction, programming and testing.

We conjectured that it would be difficult for pupils to perceive robots as integrated systems and to anticipate interactions between various parts of the robot. Most pupils in our study do not spontaneously and consciously use systems thinking to approach design, construction or programming problems and tasks. However, pupils are able to focus and reflect on separate systems and parts when they are stimulated, for example, when they have to compare slightly different robots. Systems thinking is in the zone of proximal development. Successful use of the controlled system perspective implies that pupils recognize and define relevant parts (for instance, a robot arm, a sensor, a control program, an iteration, etc.) and are aware of the relations between these entities. The robotic DME appears to be a useful educational tool to initiate explicit, conscious and systematic thinking about these relations.

We conjectured that pupils know that robots are somehow programmed by humans but will have no clear understanding of what a program really is. Pupils indeed have a notion about the existence of an internal program but initially have no idea what such a program looks like and how it functions. The DME helps them to become familiar with the programming language (blocks, parameters and values) and its purpose. Pupils were able to design simple R-A control programs. They felt that they could be in control of the robot and wanted to develop and program one on their own. Many pupils also tried to use sensors and conditional reasoning.

We conjectured that understanding how sensory input, logical reasoning processes and actions interact would be very difficult for pupils. Programming an S-R-A loop is based on the ability to analyze real world conditions and convert these into technical solutions. To "find" the white sheet of paper, the robot has to "search", and this humanoid language has to be converted to input for programmed actions. Indeed, such an analysis proved to be very difficult for pupils. When the analysis of the real world problem is phrased in more technical language pupils seem to understand the S-R-A conditional reasoning structure. However, it depends upon the complexity of the problem whether pupils are able to convert this into a program.

Conclusions and discussion

In this study, we argued that it is important for pupils, growing up in a highly technological society, to be knowledgeable ("literate") with respect to robotics. We conducted a cognitive and conceptual analysis of robotics in order to develop a frame of reference for determining pupils' understanding of robotics and designed a lesson plan that would allow pupils to develop functional technological literacy with respect to robotics. For this, we selected the Lego Mindstorms Robot, an example of a Direct Manipulating Environment.

We conclude that robotic DMEs challenge pupils to manipulate, reason, predict, hypothesize, analyze and test. Pupils compare test results with their objectives and expectations and refine their conceptual knowledge and skills constantly. This intense thinking activity is in line with previous findings (Slangen et al. 2008). The DME helps pupils to experience what a robot is, what its function is, how parts of the system depend upon each other, what control is, how control works and what a sense-reason-act loop implies.

We also conclude that learning processes with pupils aged 10–12 needs scaffolding by a teacher who asks questions, focuses attention, gives direction, deals with frustration, gives information if necessary, and helps to tackle difficult problems. Pupils' interaction with a peer and a teacher stimulated reflection and helped to build grounded and shared concepts.

In our study, the pupils learned about robots, what robots are, what they are used for, how they function, and what a robot is able to do, and in this sense they certainly became more culturally technologically literate. We showed that pupils can open a black box, an artifact that operates through unknown principles, and learn to use this device for their own objectives through an understanding of previously hidden principles. This is an important achievement in preparing pupils for modern-day technological society (Garmire and Pearson 2006). The practical activities to compare robots, to reconstruct a robot, to analyze a problem, to design, build, and program a robot helped pupils to become more competent users or practitioners of this technology. In this sense pupils developed a functional technological literacy. These pupils, we presume, will recognize robotics in everyday life and understand important concepts such as "design", "function", "system", "structure", "optimization", and "specifications" more easily (Hacker et al. 2009).

In our study we interacted with pupils on a one-to-two basis and the role of the teacher was fulfilled by a researcher. This allowed us to probe systematically various pathways towards pupils' conceptual development. In retrospective analysis, we presume we know better which phenomena attract pupils' attention and how we can organize dialogues to help pupils explicate their ideas. We know better which steps are relatively easy and which steps are complicated and require careful scaffolding. We conjecture that it is possible now to design a teaching lesson plan for use in regular classrooms, in which pupils receive far more limited teacher support. Development and investigation of such an educational practice is the focus of a forthcoming study.

Our findings come from a very specific context and deal with a small number of Dutch primary school pupils aged 11–12. Hence, wide generalization of our findings is not appropriate. We repeated the experiments with the pairs until no new patterns occurred and repeatedly checked our conclusions against the whole data set in order to discriminate a consistent pattern from singular events. We established that the pupils in our sample were able to gradually develop more advanced conceptual perspectives. We do not claim that our findings can be reproduced in the same way with other pupils, in other classes, contexts, and countries or with other age groups. We do claim that the conceptual development pathway with respect to robotics has a specific context-independent pattern and that all pupils will have to pass through conceptions that are not-yet-function, not-yet-system, not-yet-conditional, and not-yet-sense-reason-act-loop thinking. With these detailed findings, we hope to have contributed to the educational theory of teaching and learning for technological literacy in primary education.

References

Ackermann, E. (1991). The agency model of transactions: Toward an understanding of children's theory of control. In J. Montangero & A. Trypho (Eds.), *Psychologie génétique et sciences cognitives* (pp. 63–73). Geneva: Fondation Archives Jean Piaget.

Ackermann, E. (2000). Relating to things that think. *Play of Ideas and Ideas of Play, 13*, 2–4.

Alexander, R. J. (2008). *Towards dialogic teaching: Rethinking classroom talk*. York: Dialogos.

Astolfo, D., Ferrari, M., & Ferrari, G. (2007). *Building robots with LEGO® Mindstorms® NXT: The ultimate tool for Mindstorms™ maniacs*. Burlington, MA: Syngress Publishing.

Barak, B., & Zadok, Y. (2009). Robotics projects and learning concepts in science, technology and problem solving. *International Journal of Technology and Design Education, 19*(3), 289–307.

Boeijen, G., Kneepkens, B., & Thijssen, J. (2010). *Natuurkunde en techniek voor de basisschool, een domeinbeschrijving als resultaat van een cultuurpedagogische discussie (physics and technology for primary education)*. Arnhem: Cito.

Braitenberg, V. (1984). *Vehicles: Experiments in synthetic psychology*. Harvard, MA: MIT Press.

Cobb, P., & Steffe, L. P. (1983). The constructivist researcher as teacher and model builder. *Journal for Research in Mathematics Education, 14*(2), 83–94.

de Vries, M. J. (2006). Technological knowledge and artifacts: An analytical view. In J. R. Dakers (Ed.), *Defining technological literacy: Towards an epistemological framework* (pp. 17–30). New York: Palgrave Macmillan.

Dijkgraaf, R., Fresco, L., Gualthérie van Weezel, T., & van Calmthout, M. (Eds.). (2008). *De bètacanon, wat iedereen moet weten van de natuurwetenschappen (the science canon, what everyone should know about the sciences)*. Amsterdam: De Volkskrant en Meulenhoff b.v.

Dugger, W. E., & Gilberti, A. F. (2007). *Standards for technological literacy: Content for the study of technology*. Virginia: International Technology Education Association (ITEA).

Garmire, E., & Pearson, G. (Eds.). (2006). *Tech tally: Approaches to assessing technological literacy.* National Academies Press: Washington, DC.

Gifford, C. (2005). *Robots*. Haarlem: J.H. Gottmer.

Hacker, M., & Burghardt, D. (2008). *Technology education. Learning by design* (Revised ed.). Boston, MA: Pearson Prentice Hall.

Hacker, M., de Vries, M. J., & Rossouw, A. (2009). *CCETE project, concepts and contexts in engineering and technology education (No. DUE 0314910)*. New York, Delft: Hofstra University and Delft University of Technology.

Hamner, E., Lauwers, T., Bernstein, D., Nourbakhsh, I., & DiSalvo, C. (2008). *Robot diaries: Broadening participation in the computer science pipeline through social technical exploration*. Paper presented at the AAAI Symposium on Using AI to Motivate Greater Participation in Computer Science. Retrieved November 8, 2009 from www.aaai.org/Papers/Symposia/Spring/2008/SS-08-08/SS08-08-008.pdf.

Hodson, D. (1992). In search of a meaningful relationship: An exploration of some issues relating to integration in science and science education. *International Journal of Science Education, 14*, 541–562.

Jenkins, E. W. (1990). Scientific literacy and school science education. *School Science Review, 71*(256), 43–51.

Johnson, S. D. (1997). Learning technological concepts and developing intellectual skills. *International Journal of Technology and Design Education, 7*(1–2), 161–180.

Jonassen, D. H. (2006). *Modeling with technology, mindtools for conceptual change* (3rd ed.). Columbus, OH: Pearson Prentice Hall.

Jones, A., & Moreland, J. (2004). Enhancing practicing primary school teachers' pedagogical content knowledge in technology. *International Journal of Technology and Design Education, 14*(2), 121–140.

Kipperman, D. (2009, August 24–28). *Teaching through technology concepts*. Paper presented at the Strengthening the Position of Technology Education in the Curriculum; PATT-22 Conference, Delft, Netherlands.

Krumholtz, N. (1998). Techno-logic: A micro-world for constructivist science and technology learning [electronic version]. *ICCE98*. Retrieved 2006 6, May from http://www.phantom2.com/papr_tch.html.

Levy, S. T., & 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*(4), 337–359.

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

Mioduser, D., Venezky, R. L., & Gong, B. (1996). Students' perceptions and designs of simple control systems. *Computers in Human Behavior, 12*(3), 363–388.

Moens, G. (2008). *Technische geletterdheid voor iedereen; standaarden en referentiepunten (Technological literacy for everyone: Standards and reference points)*. Departement van Onderwijs en Vorming and Departement van Economie Wetenschap en Innovatie; Vlaanderen.

Pearson, G., & Young, A. T. (Eds.). (2002). *Technically speaking: Why all Americans need to know more about technology*. Washington, DC: National Academy Press.

Petre, M., & Price, B. (2004). Using robotics to motivate "Back Door" learning. *Education and Information Technologies, 9*(2), 147–158.

Resnick, M., & Martin, F. (1991). Children and artificial life. In I. Harel & S. Papert (Eds.), *Constructionism* (vol. 10, pp. 379–390). Norwood, NJ: Ablex Publishing.

Rocard, M. (2007). *Science education now: A renewed pedagogy for the future of Europe*. Luxemburg: Office for Official Publications of the European Communities.

Savage, T., Sánchez, I. A., O'Donnell, F., & Tagney, B. (2003). *Using robotic technology as a constructionist mindtool in knowledge construction.* Paper presented at the ICALT'03.

Shin, N., & Kim, S. (2007, August 26–29). *Learning about, from, and with robots: Students' perspectives.* Paper presented at the 16th IEEE International Conference on Robot & Human Interactive Communication, Jeju, Korea.

Slangen, L. A. M. P., Fanchamps, L. J. A., & Kommers, P. A. M. (2008). A case study about supporting the development of thinking by means of ICT and concretization tools. *International Journal of Continuing Engineering Education and Lifelong Learning, 18*(3), 18.

Slangen, L. A. M. P., van Keulen, J., & Jochems, W. (2009). De bijdrage van direct manipulation environments aan de ontwikkeling van technische geletterdheid in de basisschool (The contribution of direct manipulation environments on the development of technological literacy in primary education). In J. van Keulen & J. Walma van der Molen (Eds.), *Onderzoek naar wetenschap en techniek in het Nederlandse basisonderwijs (Research on science and technology in Dutch primary education)* (pp. 115–130). The Hague: Platform Bèta Techniek.

Strauss, A. L., & Corbin, J. (1990). *Basics of qualitative research: Grounded theory procedures and techniques*. Newbury Park, CA: Sage.

Sullivan, F. R. (2008). Robotics and science literacy: Thinking skills, science process skills and systems understanding. *Journal of Research in Science Teaching, 45*(3), 373–394.

ter Horst, M., Dannenburg, W., van Boxtel, R., & Horn, E. (2008). Thema 2: Techniek om ons heen (Theme 2: technology around us). In M. van Ooijen (Ed.), *Naut natuur en techniek, Lesboek (Naut nature and technology, instruction book)* (pp. 50–71). 's-Hertogenbosch: Malmberg BV Bao.

van Eijck, M. (2008). *Scientific literacy: Past research, present conceptions, and future developments. Worlds of Science Education Handbook: North America*. Rotterdam: Sense.

van Graft, M., & Kemmers, J. (2007). *Onderzoekend en ontwerpend leren bij natuur en techniek (inquiry and design learning for nature and technology)*. The Hague: Stichting Platform Bèta Techniek.

van Lith, P. (2006). *Masterclass Robotica*. Limbricht: Elektuur.

Vanderborght, B. (2008). *Robots, binnenste buiten (Robots, inside out)*. Sint-Niklaas: Uitgeverij Abimo.

Verlaan, B., 't Veld, R., van der Veen, H., van Rij, V., Morin, P., & Maassen van den Brink, H. (Eds.). (2007). *Rapport horizonscan 2007, naar een toekomstgerichte beleids- en kennisagenda (report horizonscan 2007, to a forward-looking policy and knowledge agenda)*. The Hague: Commissie van Overleg van sectorraden voor onderzoek en ontwikkeling, COS.

Vygotsky, L. (1986). *Thought and language* (A. Kozulin, Trans. Revised ed.). London: MIT Press.

Walma van der Molen, J., de Lange, J., & Kok, J. (2009). Theoretische uitgangspunten bij de professionalisering van leraren basisonderwijs op het gebied van wetenschap en techniek (Theoretical principles for professionalizing primary education teachers in the field of science and technology). In H. van Keulen & J. Walma van der Molen (Eds.), *Onderzoek naar wetenschap en techniek in het Nederlandse basisonderwijs (research on science and technology in Dutch primary education)* (pp. 53–66). The Hague: Platform Bèta Techniek.

Wisse, M. (2008). Robots, sensoren, algoritmes en motoren (robots, sensors, algorithms and engines). In R. Dijkgraaf, L. Fresco, T. Gualthérie van Weezel, & M. van Calmthout (Eds.), *De bètacanon, wat iedereen moet weten van de natuurwetenschappen (the science canon, what everyone should know about science)* (pp. 185–187). Amsterdam: De Volkskrant en Meulenhoff b.v.

Zuga, K. F. (2004). Improving technology education research on cognition. *International Journal of Technology and Design Education, 14*(1), 79–87.