Teaching robotics in primary school

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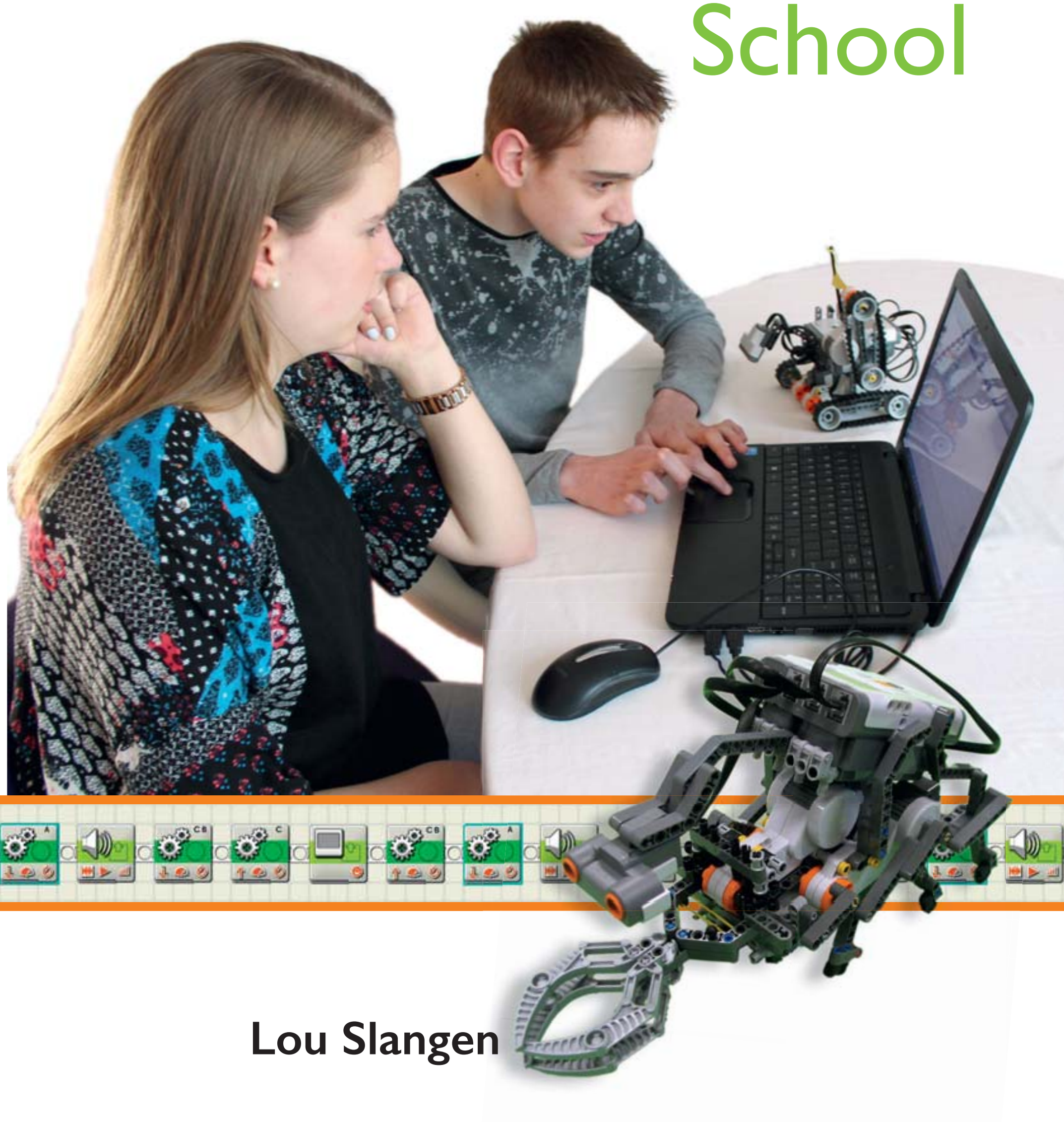

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Het onderzoek dat in dit proefschrift wordt beschreven is uitgevoerd in overeenstemming met de TU/e Gedragscode Wetenschapsbeoefening.

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Chapter 1: General Introduction

1.1 Background to the study

Two innovation movements in Dutch primary schools may be considered as the backgrond to this study on "teaching robotics in primary school": the implementation of Information Communication Technology; and the implementation of Science and Technology. Robotics is a relevant topic from both perspectives and is likely to gain increasing interest from educators, as it is expected to contribute to students' technological literacy development (Schnabel, 2016; Went, Kremer, & Knotterus, 2015) and has impact on their future.

1.1.1 Science and technology in Dutch education

Since the introduction of computers in Dutch schools in the middle of the 1980s, we have seen an enormous evolution in the variety and potential of ICT tools that are available for pedagogical use. ICT has shown to offer many opportunities to develop, innovate and optimise educational practices. In the UNESCO report of Kalaš et al. (2012, p. 18) ICT in education is referred to as "…. a collection of computer-based technologies, which are exploited to support teaching and learning, communication and collaboration, self-expression, creation, etc., that is, for the promotion of all developmental domains of children, and learners of any age." This quote underscores that depending on the kind of tools and their application, ICT can serve many educational goals. It can be used, for example, to enhance instruction, stimulate creative self-expression, support students' learning and thinking, facilitate problem solving and modelling, stimulate collaborative learning, or support students in learning to program. These skills are part of the so-called 21st century skills, and ICT literacy is often mentioned as a key skill (Voogt & Pareja Roblin, 2010). More specifically, ICT might be employed to foster various technological and scientific thinking skills, such as categorising, thinking in terms of variables, understanding cause-and-effect, means-end, and function-realisation relationships, visualising, schematising and modelling (Baartman & Gravemeijer, 2011).

Since the end of the 1990s, Dutch primary schools are expected to develop and implement science- and technology education. It is argued that Western countries need many more highly educated workers in the fields of technology, and science- and technology education should support students in becoming active participators in a technological world. We should, therefore, make sure that students become scientifically and technologically literate (Dugger & Gilberti, 2007), and feel comfortable with technology by the time they leave school (Rogers & Portsmore, 2004). Curriculum scholars translate this general goal into tangible descriptions, such as the Standards for technological literacy (Dugger & Gilberti, 2007), the Dutch domain description by Boeijen, Kneepkens, and Thijssen (2010), or the curriculum framework by van Graft, Klein Tank, and Bakker (2014). In Dutch primary education the use of the term "science and technology" is multi-faceted (van Graft et al., 2014). It refers to both the skills needed in the context of investigating, or designing and engineering, and to the corresponding attitude of "wonderment" and curiosity. The term is also used to describe the domain (Greven & Letschert, 2006). Further, "science and technology" is associated with inquiry-based learning and design- and engineering-based learning (van Graft & Kemmers, 2007), which are pedagogies that can be applied in many other disciplines as well. In order to speed up the adaptation and implementation of science and technology in primary schools, several national science and technology programs have been launched, however, the effect of these efforts in primary schools is still small (Clevers & Willems, 2013). Teachers sometimes attribute themselves lack of skills and knowledge (Inspectie van het onderwijs, 2005; Rohaan & Slangen, 2014). Such a shortage can refer to different aspects, for instance, content knowledge, pedagogical content knowledge, or, practical skills with respect to inquiry and design. Further, teachers may feel insecure with respect to their teaching capabilities in terms of science and technology. At times teachers may lack specific techniques (questioning, scaffolding, guiding, et cetera) needed for supporting their students, and conducting collaborative inquiry and problem based learning.

The term technological literacy also needs some discussion. This term is often used as synonymous with being technologically competent (Barnett, 1995). However, the two are not the same. Although technological literacy includes some hands-on practical skills, this concerns the lower level of the skill scale (Garmire & Pearson, 2006). Literacy can be conceptualised as a range of social practices, which entail reading and writing but also involve communicating, reflecting and thinking, observing and operating for a wide range of purposes (Hackling & Prain, 2005). According to (Waetjen, 1993, p. 9) technological literacy is not an "all- or none learning and should not be described in such terms". Technological literacy occurs along a continuum with types and levels of literacy varying according to age and needs of the particular population (Garmire & Pearson, 2006). We therefore define technological literacy as having some understanding of technology that enables one to use and design simple technology. This definition indicates that technological literacy not just refers to knowing and understanding, but also to using and applying. Basically, technological literacy refers to students' knowledge and skills, and an appreciation of the purposes that technology can serve, how it can be used efficiently and effectively to achieve these goals. We notice a growing awareness of the necessity to pay more attention to the application of ICT in primary schools, not from a consumer's but from a producer's point of view (Maas, 2015). Hence, it is appreciated that learning and teaching with and about robotics may contribute to students' technological literacy.

1.1.2 Teaching robotics in the primary school

Teaching robotics in primary school, so some argue, finds its origin in the work of Seymour Papert at MIT in Cambridge. He investigated the educational value of programming an object which he named "Turtle". Papert was primarily interested in this tool as an "object-to-think-with" (Ackermann, 2001, p. 4). The Turtle was an electromechanical device able to drive in any 2D direction and to draw lines, with a pencil that could be lowered or lifted. The turtle was, with respect to present days' standards, a simple automat directly controlled by an easy to understand programming language named "Logo". Notwithstanding the latter, the programming language allowed students to learn about geometry, serial and parallel processes, principles of programming such as recursion, while gaining pleasure from playing with the Turtle. The Turtle served as a tool, to program and to think with. Since drawing by having the Turtle riding over a sheet of paper was very time consuming, using a computer screen to draw images became popular.

In the 1980s Kjeld Kirk Kristiansen (CEO of LEGO Company) was stimulated by the work of Papert. Papert's ideas about children's learning by manipulating objects, and LEGO's philosophy of building and controlling devices with motors and gears matched well. Papert (1993) developed the theory of constructionism which merged two ideas: the constructivist theory where learning is understood as a (re)construction (rather than as a transfer of knowledge); and the idea that learning is more effective when the learner constructs a tangible and meaningful product (Papert, 1993; Resnick & Ocko, 1990). The collaboration of Papert, the MIT, and the LEGO Company proved fruitful and led to the development of the Logo programming language for the first programmable LEGO "Brick" that made use of sensors and actuators and was able to use sensory input to decide about actions. The foundation for further collaboration was laid and the LEGO/Logo environment was optimised to be suitable for schools (Resnick, Ocko, & Papert, 1988). The programmable brick (RCX) was integrated into the LEGO building blocks and new programming environments (RCX code or ROBOLAB) were developed. At the end of the

1990s the LEGO Company released this RCX Mindstorms robotic kit and RCX programming code for use in education. The programmable brick came with several kinds of sensors (sound, touch, light, distance), servo motors, software and building materials. This material moved programming back (away from the screen) into the physical world. Now children could also design and construct robots (Resnick & Ocko, 1990; Resnick et al., 1988). Since the first RCXs two more generations (NXT and EV3) have been produced. Several other enterprises have also developed comparable educational products, such as the brick “Leonardo” and software “Techno-Logica” (see chapter 3) or PCS Edventures Discover Robotics & Programming Kit. Fischertechnik developed several products, for instance the “ROBO LT Controller” and “ROBO PRO Light”. As a result of the “First LEGO League” challenge, the LEGO/Logo environment became very popular all over the world. However, it seemed to be mostly used in out-of- or after-school projects, rather than as a part of the regular science and technology curriculum of the primary school.

By the time the LEGO Mindstorms NXT was released in 2006, there was a strong governmental drive to introduce technology in primary education. From this moment on we have seen an initially hesitant but then increasing interest in the use of robotics as a tool to learn from, to learn with and to learn about. Teaching robotics seems to be a fruitful educational approach, as it integrates two areas of attention; ICT and Technology. Moreover, it appears to be an adequate means for engaging students in developing deeper understandings and skills in the domain of ICT and technology.

The scientific literature addresses many different questions about the potential value of such tools in areas such as problem solving, technical fluency, learning by design, self-reflection, collaboration, self-confidence, cognitive, social, and emotional learning (Bers, Ponte, Juelich, Viera, & Schenker, 2002; Kärnä-Lin, Pihlainen-Bednarik, Sutinen, & Virnes, 2006; Krumholtz & Markuze-Haas, 1998; Lavonen, Meisalo, & Lattu, 2001; Lindh & Holgersson, 2007; Savage, Sánchez, O'Donnell, & Tagney, 2003; Sutinen, Virmajoki-Tyrväinen, & Virnes, 2005). Some researchers claim that these tools can be used to attain goals in the domains of engineering, mathematics, physics, science and technology (Krumholtz, 1998; Lavonen, Meisalo, & Lattu, 2002; Petre & Price, 2004; Rogers & Portsmore, 2004). Others report on studies about learning to program and to understand concepts of programming (Demo, Marcianò, & Siega, 2008). Cajas (2002) argues that within the technology education community admittedly technological skills and concepts to learn are identified, but more research has to be conducted to understand how these are taught and learned best.

Understanding how students learn and teachers teach robotics raises questions with respect to needed or useful conditions, kinds of material, conceptual and social resources, and on how cognition relates to this technological content

The general assumption is that construction tools with which robot models can be built and manipulated engage students' interest in technology and increase their technological literacy. Building, programming and manipulating robots might give students a sense of connecting with the real, out of school, life. They can immediately see the effects of their interventions, and can directly make desired changes. The manipulative nature of the models may evoke a kind of gaming experience. Such tools can support and encourage new ways of thinking, and exploring of, the real world (Sargent, Resnick, Martin, & Silverman, 1996).

1.2 Problem statement, research design and methods

The use and impact of robotics on our daily life has been increasing fast. Boeijen et al. (2010) emphasise that learning about concepts of automation is an important educational subject for today's primary school. This underscores that there is a need to understand more about the potential aims and ways of teaching robotics, especially in the higher grades of primary school. A literature search, however, showed that the number of empirical studies on this topic was small.

Therefore our main research topic concerned the question: *"How can robotics be taught and learned in the context of a regular primary school grade 6*[*]

This general research idea debouched into four independent design experiments. The studies were qualitative and explorative in nature aiming to probe lesson designs and to understand more about students' and teachers' learning processes in the context of robotics. Although we speak of design experiments, we did not develop one pedagogical design, which was improved through several iterative cycles, which is an often-used method in design research. Instead we developed different designs for each sub-study and used these to come to understand more about specific aspects of learning and teaching robotics. However, even though we used different forms of design based experiments, they all entailed the need to "engineer" particular forms of teaching and learning and to systematically study the resulting teaching-learning processes within specific contexts (Cobb, Confrey, Disessa, Lehrer, & Schauble, 2003). Each study originated from and

[*] In this dissertation we used the US grade level system to indicate the research population. Grade 6 corresponds with what is called "groep 8" in the Netherlands.

builds on the previous study. The studies of this project could be characterised as design based research as they included a variety of characteristics mentioned by van den Akker, Gravemeijer, McKenney, and Nieveen (2006), such as intervening in a realistic educational setting; focussing on objects and processes in a specific context; being theory-oriented; and developing conjectures about student learning and the teacher's role in order to come to understand and improve the design. The four empirical studies were preceded by a literature study, which examined how a learning environment in primary school could be enhanced by using ICT as mind tools (Jonassen, 2000, 2006; Jonassen, Carr, & Hsiu-Ping, 1998; Krumholtz & Markuze-Haas, 1998) which allows students to manipulate technology in such a manner that it fosters reasoning and knowledge development. This sets the scene for the empirical studies, each addressing a research question, which emerged from the progression in the research project. These specific research questions were:

1. How can solving problem based programming tasks activate students' thinking behaviour by using a hybrid micro world?
2. What can students learn from working with robotic direct manipulation environments?
3. How do primary school teachers develop the ability to support students' inquiry- and design-based learning of robotics?
4. How does a local instruction theory for teaching about robotics in primary school develop?

We now provide an overview of each of the four empirical studies with respect to the context, its particular design, and the data collection and analysis strategies used. As the studies were exploratory by nature, the data collection strategies of the different studies were qualitative, with the purpose of gaining deeper understandings and insights into the practice of teaching robotics in school. We used selected methods depending on the question of study in use. As such, we positioned our studies as contributing to mapping the terrain of teaching robotics in primary school, with the purpose of developing local theory.

Study 1: How can solving problem based tasks by programming a hybrid micro world activate students' thinking behaviour? (see chapter 3)

Context

The idea for this study emerged from experiences of a pre-service teacher, who participated in a study group on ICT and technology and engineering. He noticed that students of his grade 6 class were highly engaged and intensely reasoning (thinking) with each other when they could solve realistic problems manipulating concrete digital tools such as Sim City. A literature study was performed and it became clear that this observation was in line with the finding that many types of digital tools were, arguably, of use to stimulate students' reasoning and thinking through problem based learning (Jonassen, 2006; Jonassen et al., 1998; Slangen & Sloep, 2005). Actually, the interest of the research group focussed on the exploration of the educational use of concrete hybrid tools, which combined the material and the digital world, such as Techno-Logica. The theoretical construct of mind tools appeared to be of use to develop an empirical study to answer the research question: *How can solving problem based tasks by programming a hybrid micro world activate students' thinking behaviour?*

This general research question was subsequently elaborated into the following sub questions:

1. *Is Techno-Logica a useful mind tool to construct teacher independent Problem Based Learning environments?*
2. *Can we recognise active higher-order thinking and habits of mind in such learning environments?*
3. *Which types of higher-order thinking can we discern?*

Research design

As a result of discussions in the research group it seemed best to investigate students' thinking by analysing the discourses taking place in concrete problem solving cases. These cases were instrumental, as they were of use to illuminate students' thinking behaviour (Creswell, 2008). The actual study was situated in a school grade 6 class in the south of the Netherlands in the city of Heerlen.

We decided to focus on student verbal and non-verbal utterances as means to interpret types of thinking, because thinking is known to be more than speaking (Boostrom, 2005). In order to evoke high engagement and to stimulate intensive student interaction and dialogue (Strom & Strom, 1999), we organised that the students worked in pairs and mainly teacher independently. To prevent that students quitted the task when they became stuck, a pre-service teacher was present to give hints and encourage students when necessary. To organise this form of problem-based learning a design based learning experiment was developed and conducted. We designed a pedagogical setting in which the pairs were provided with the concrete tools and predefined problems to solve. We used the mind tool Techno-Logica, which consists of a Programmable Logical Controller (PLC), control software, and a material part consisting of sensors, actuators and constructions. Students were provided with a small booklet which consisted of three parts: (1) a short instruction on programming, (2) a problem task with respect to programming an automat (a traffic light), and (3) a problem task with respect to programming an autonomous machine (a Ferris wheel). The booklet and the problem tasks were trialled by pre-service teachers in several separate test runs conducted prior to the experiment. Insights from these trials were used to optimise the booklet and problem tasks.

Data collection

Twelve primary school students (in pairs) were provided with the booklet and first conducted the introductory part. Successively, in two separated sessions, the two problem solving tasks were conducted. Students worked on the tasks until the problem was completely solved. The complete sessions of problem solving of both tasks were video-recorded for each pair.

Table 1.1: Study 1 overview of the research questions, data collection and data analysis

Study 1	Research questions	Data collection strategies	Data analysis strategies
	How can solving problem based tasks by programming a hybrid micro world activate students' thinking behaviour?		
	1. Is Techno-Logica a useful mind tool to construct teacher independent PBL?	- Video recording the student pairs' reasoning about how to solve (program) both problem tasks. - Developing a check list for scoring characteristic problem solving behaviour	- Observing behaviour on video recordings and scoring the characteristic activity (each minute)
	2. Can we observe active higher-order thinking and habits of mind in such learning environments?		- Observing indicative behaviours and noting characteristic utterances (all recordings each minute) - Observing speech and activity - Scoring the four most characteristic thinking skills by using the checklist (each minute, all recordings) - Scoring the four most characteristic habits of mind by using the checklist (each minute, all recordings)
	3. Which types of higher-order thinking can we discern?		- Totalising the different types of scores Habits of Mind

			- Totalising the different types of scores Thinking Skills - Totalising over categories of Thinking Skills

Data analysis

Observing video recordings and scoring characteristic activities each minute showed the main student activities and the degree of the teacher support. Because we were mainly interested in the extent and the kind of thinking behaviour we focussed on both qualitative and quantitative elements. We first gathered qualitative data to explore the phenomenon of thinking, and quantified the data by means of systematic and structured scoring of the utterances of the students with two checklists. In order to do this, we developed a checklist based on a selection of relevant categories in the domain of thinking skills based on the IOWA thinking model (Iowa Department of Education, 1989; Jonassen et al., 1998) and the habits of the mind model (Costa, 2000). The checklist consisted of 16 kinds on habits of mind and 18 kinds of thinking skills. The definition of the categories was described in a list. Every minute of the process the most distinct content related expressions were coded with categories of the two checklists (four expressions on thinking skills and four on habits of minds). The first author checked the selected characteristic utterances against the second author of this study and differences were discussed until agreement was reached. The same procedure was used with respect to coding of the Habits of Mind. Because our study was explorative in nature the outcome of these scores were meant to find trends and indications for future research. As the study was exploratory with respect to the topic of thinking behaviour, we had initially no clear idea how students would execute this task and what could be said about higher order thinking.

Study 2: What can students learn from working with robotic direct manipulation environments? (see chapter 4)

Context

From the first study we knew that students can solve the programming problems of an automaton and an autonomous machine (robot) through manipulating concrete materials and by reasoning and thinking about the working of the program (Slangen, Fanchamps, & Kommers, 2008) (see Chapter 3). The research team discussed these findings and the question arose about what students actually learn about robotics when they are manipulating such a robotic environment. It was argued that from a societal point of view it is important that people in general become more literate (knowledgeable and skilled) with respect to robotics, since robotics will be everywhere in future society. Hence, it is relevant to study the theoretical and practical contributions of teaching and learning robotics in school. What students learn about robotics can be approached from two standpoints. The first is how experts conceptualise robotics and what they think students can learn; the second is what students in an educational setting actually demonstrate to be able to learn when working with robots. Therefore, the general research question was formulated as: *What can students learn from working with robotic direct manipulation environments?*

Two sub questions were derived:

1. *What do students 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 students' conceptual understanding of robotics develop, in the context of robotic problems that are offered through a Direct Manipulation Environment?*

Research design

The design of this study had two aims: first, it aimed at developing existing tacit and explicit knowledge into a conceptual framework that is consistent with public and expert views on robotics; and second, at developing and testing emerging theory to understand what students actually learn. Consequently, we used a two-step approach: (1) a conceptual analysis was executed in the form of a content related literature study and the drawing of a robotic concept map. This was discussed in the research team and successively reduced into four major concepts. (2) An exploratory intervention in the form of a teaching experiment was conducted. Six pairs of students (who were selected on the basis of their eloquence) participated in several lessons conducted by the first author on robotics in an inquiry and reconstruction based dialogic approach. The researcher acted as a teacher who presented the robotic problems to solve, asked questions and in general stimulated students' discourse and problem solving behaviour. The students were provided with robotic tools (LEGO Mindstorms) and were invited to inquire, discuss, compare, probe, et cetera. The actual study was situated in a primary school grade 6 class in the south of the Netherlands in the city of Roermond.

Data collection

The complete sessions of problem solving of both tasks were video-recorded for each of the six pairs. Students' programming on the computer was screen-captured in combination with a picture in picture (PIP) presentation of the webcam.

Table 1.2: Study 2 overview of the research questions, data collection and data analysis

Study 2	**Research questions**	**Data collection strategies**	**Data analysis strategies**
	What can students learn from working with robotic direct manipulation environments?		
	1. What do students understand of robotics, that is, what perspectives and (key) concepts do they use to describe their knowledge, experiences and understanding of robotics?	Step 1 - developing a content specific analysis on robotic concepts from a literature analysis. Step 2 (developing and conducting in a dialogic manner a lesson plan about robotic concepts in a one to two teaching experiment) - Video recording the lessons (students' discussions, practical activities and the programming actions) - Screen capturing the programming and by PIP combining this with students dialog.	Step 1 - developing a concept map on robotic concepts - identifying main concepts through professional dialog Step 2 (after importing the recordings in Atlas.ti) - Analysing the video data, identifying and scoring emerging labels to events and issues on the video fragments and transcribing explanatory fragments (Atlas.ti) (groups 1-3 lesson 1-6) until saturation (no new labels emerged) - Transforming labels into four emerging perspectives and testing these against the dataset (groups 1-6 lesson 1)
	2. How does the students' conceptual understanding of robotics develop, in the context of robotic problems that are offered through a DME?		- Analysing the raw data for descriptions and video fragments that support the sub questions and conjectures. - Analysing the raw data set through matching concepts and perspectives with the

	a. How do students conceptualise robots? b. Are students able to develop a functional point of view? c. Do students perceive robots as integrated systems? d. Do students understand that robots are controlled by a program? e. Are students able to understand and apply the Sense-Reason-Act loop?		fragments demonstrating this. - Searching and tagging illuminating and explanatory fragments, which underscore the theoretical description.

Data analysis

Based on a literature search about designing and building robots, a conceptual analysis was conducted resulting in a functional concept map, which was discussed in the research group. This professional discussion led to deducing four theoretical concepts relevant for developing teaching materials and for use as the language for referring to what students learn.

To understand what students may learn from working with robotics the video data were studied retrospectively, by a modified version of the constant comparative data analysis (Glaser & Strauss, 1967). The raw data were analysed several times to indicate fragments, which appeared to be relevant with respect to students' developing understanding of robotics. With Atlas.ti these fragments were tagged with emerging labels describing the main activity in relation to a specific conceptual development of that fragment. When no new relevant labels seemed to emerge it was concluded that a point of saturation was reached and the labelling was ended. The labelling was discussed with the second author of this study until agreement was reached. In a next step the labels were analysed to find indications for trends, which led to defining four emerging perspectives students seem to use to make sense of their experiences (the psychological, technological, function, and controlled system perspective). In a next round of comparing, these four perspectives were tested against the dataset of the lessons of all (six) groups. The occurrence of the different perspectives was quantified in absolute numbers and in percentages to find indications on the prevalence of the perspectives.

Interpreting these perspectives in terms of a progressive conceptual development of students learning throughout the lessons gave rise to an understanding of what students learned from working with robotics. To check this interpretation, video fragments were tagged with the perspective and/or concept labels from the previous theoretical conceptual analysis. Introducing such additional information is not very common in the Constant Comparative Data Analysis method (Glaser & Strauss, 1967), but lack of this is also a point of criticism (Silverman, 2006). This, in combination with our analysis approach, is why we speak of a modified version of this method. Video fragments contributing to an explanatory theory on students' conceptual development with respect to the different perspectives and concepts were used to illustrate the lines of argumentation.

Study 3: How do primary school teachers develop the ability to support students' inquiry- and design-based learning of robotics? (see chapter 5)

Context

In the first study of this research project we found that students could solve programming problems through reasoning, thinking, and manipulating concrete robotic materials (Slangen et al., 2008) (see chapter 3). The second study illuminated that students could develop conceptual knowledge while working with robotic Direct Manipulation Environments (DME) (Slangen, van Keulen, & Gravemeijer, 2011b) (see chapter 4). Both studies made clear that students, to some extent, can learn robotics by themselves, but that teacher support was needed with regard to selected aspects. The support was not only necessary to overcome deadlock situations, which may be regarded as trivial from a theoretical point of view. But support was also necessary to deepen students' conceptual understanding. In the first two studies we focused on how to design a teaching lesson plan for use in regular classrooms, where students could only receive limited teacher support. Theoretically, a teacher has various ways to scaffold, stimulate and extend students' thinking and advance their learning and understanding, for example, by asking questions, by motivating, focus attention, providing feedback, dealing with frustration, pointing out inconsistencies, giving direction and elaborating on experiences and information (Alexander, 2008). However, from our experience in the previous studies, our experience with pre-service and in-service teacher training and from literature on STEM in primary classrooms (Rohaan & Slangen, 2014; van der Wel & Krooneman, 2014; Walma van der Molen, Aalderen-Smeets, & Asma, 2010) we deduced that most teachers would not be prepared for teaching robotics in school in such a way that conceptual understanding was likely to develop. Therefore, we investigated whether it was possible to prepare teachers adequately to implement the intended pedagogy, with the help of an in-service teacher education course that we developed. From this, the third general research question arose: *How do primary* *school teachers develop the ability to support students' inquiry- and design-based learning of robotics?*

More specific four sub questions were formulated.

1. *How do teachers acquire the subject matter knowledge (SMK) they need?*
2. *How do teachers elaborate their existing pedagogical knowledge (PK) into an approach that suits the requirements of inquiry- and design-based teaching, i.e. a scaffolding approach?*
3. *How do teachers develop pedagogical content knowledge (PCK) that will allow them to help students construct understanding of the concepts function, system, control and sense-reason-act?*
4. *How does the professional development trajectory influence teachers' attitudes and self-efficacy with regard to teaching robotics in class?*

Research design

The design of this study was based on the development and execution of a professional development program for (in-service) teachers. The program was built on experiences and tools from the previous pedagogical designs and from general course development experiences of the researcher. The course offered 1) subject matter knowledge on designing and programming a robot and on solving robotic problem tasks; 2) pedagogical knowledge on scaffolding robotic problem solving and analysing video recorded practices; 3) pedagogical content knowledge on how students come to understand robotic concepts and perspectives and their predispositions and difficulties when working with robotics; and 4) practical modelling of the role of the teacher by the course leader. The course consisted of four sessions, which were supported by a teacher guidebook containing information and tasks, robotic tools and additional materials such as supplementary texts, links to internet sites and videos, for example.

The actual course was conducted by the researcher and delivered to two comparable groups of in-service teachers. Fifteen primary school teachers (seven male and eight female) with an average of 17 years of teaching experience ranging from one to 36 years participated. The teachers were recruited from schools in the southern province of Limburg in the Netherlands. Most of these teachers did not have any experience of teaching robotics but were interested to increase their personal knowledge and skills and to learn how to teach robotics in school.

Data collection

Data were gathered in the form of answers to semi-structured questionnaire items, mind maps and notes taken by the participants, and video and audio recordings of the meetings. By means of a member check the interpretations were validated.

Table 1.3: Study 3 overview of the research questions, data collection and data analysis

Study 3	Research questions	Data collection strategies	Data analysing strategies
	How do primary school teachers develop the ability to support students' inquiry- and design-based learning of robotics?		
	a. How do teachers acquire the subject matter knowledge (SMK) they need?	(The researcher conducted four lessons following the trajectory of a guide/note book.) - The notes about the lessons, experiences, opinions and results to tasks were written down in the guide/note book. - A pre- and post-questionnaire was included to collect data about the whole trajectory. - Video recordings of teachers' practical work during the trajectory were made. - Member checks were conducted	- Teacher notes, questionnaire answers, video/audio recordings were tagged with labels indicating the topic. - Quantitative analysis of frequencies of labels to find trends or indications for developing SMK, PK, and PCK - The pre- and post-questionnaire answers were qualitatively compared - Mind maps were analysed - Member check reactions were clustered and compared to optimise the interpretations.
	b. How do teachers elaborate their existing pedagogical knowledge (PK) into an approach that suits the requirements of inquiry- and design-based teaching, i.e. a scaffolding approach?		
	c. How do teachers develop pedagogical content knowledge (PCK) with respect to function, system, control and sense-reason-act?		
	d. How does the professional development trajectory influence teachers' attitudes and self-efficacy with regard to teaching robotics in class?		

Data analysis

We collected raw data such as teacher notes, questionnaire answers, mind maps, and video/audio recordings. These materials were analysed (a) to enable qualitative retrospective analysis (Cobb et al., 2003) of the participants' subject matter knowledge, pedagogical knowledge (i.e. scaffolding skills) and pedagogical content knowledge, (b) to understand the rationales for development of these forms of knowledge, and (c) to estimate the possibilities and limitations of teaching robotics by these teachers in their primary schools. The aim was to explore and develop relevant notions and ideas to form a local theory about how to prepare teachers to teach robotics. To achieve this, the raw data were transcribed into text data. These data were imported in Atlas.ti and text fragments were tagged with indicative labels. We totalised the tags and conducted a summative content analysis (Hsieh & Shannon, 2005). The quantified labels were used to analyse the summative findings in a search after process or content aspects. Successively, in the research team a process of latent content analysis was conducted by interpretation of the texts. This process aimed at exploring the texts to find and understand trends or signs. We compared and discussed these in the research team against the background of our conceptual framework of learning and teaching robotics. Mind maps drawn at the start of the first meeting (MM1) and redrawn in the last meeting (MM2) provided additional information on teacher knowledge and how teachers related various aspects of robotics to each other. Questionnaires were used at the beginning and the end of the programme. Initial answers (Q1) were compared with the final answers (Q2) in order to detect changes and developments with regard to knowledge of robotics, knowledge of students' conceptions and ideas on effective teaching. Video/audio recordings (VR, AR) allowed for analysis of teachers' activities and spontaneous reactions to the assignments and questions. Teachers' behaviour was also compared with the way students reacted to similar assignments in the previous study (Slangen et al., 2010). These qualitative analyses led to notions that could be combined to form a local theory on the activities and situations that provoke the development of relevant SMK, PK and PCK. We compared these notions against the data set in order to find supportive utterances for the interpretations and conclusions. The notions were written down as an interpretive preliminary text about how to prepare teachers to teach robotics.

By means of a member check (Robson, 2002; Silverman, 2006) the teachers validated the general notions. Ten of the fifteen participants responded and agreed with the texts. The main reason for non-response was lack of time, not disagreement. We concluded that, in principle, it is possible to prepare teachers for teaching robotics in regular classroom settings.

Study 4: Why did the students not reach the intended level of understanding of robotics? (see chapter 6)

Context

From the previous studies of this research project we know that students can learn about general robotic concepts and can solve robotic problems through reasoning, thinking, and manipulating concrete robotic materials (Slangen et al., 2011b; Slangen et al., 2008) (see chapter 3&4). These studies helped to understand better what seemed to be of relevance when designing a lesson plan for teaching and learning robotics in a regular school class. It also proved to be possible to prepare teachers for supporting students' learning robotics. (Slangen, van Keulen, & Gravemeijer, 2011a) (see chapter 5). For this purpose, the teachers conducted activities and experienced situations that provoked the development of relevant SMK, PK and PCK. At this point in our research project we decided to have enough content and process knowledge to develop and test a pedagogical design on teaching and learning robotics which could be executed in a regular primary school under more or less representative conditions. Our aim was to execute a teaching experiment to investigate and improve a local instruction theory about teaching and learning robotics with a focus on understanding students' learning trajectories and teachers' roles in conducting reflective dialogues. For this purpose, we initially planned to conduct a design research project to answer the question; *How to develop a local instruction theory for teaching robotics in primary school?* However, during the retrospective analysis we found that the initial goals of the learning trajectory were only partly reached and the central research question shifted into: *Why did the students not reach the intended level of understanding of robotics?* The new research question triggered a retrospective analysis that led to several emerging conjectures.

Research design

In order to study the students' conceptual development and the role of the teacher in an ecologically valid situation, a teaching experiment for execution under representative conditions was designed. We developed a teacher independent learning trajectory for the students and orchestrated reflective discourses between students and teacher. For this purpose, a teacher independent guidebook with informative texts, various links to robotic videos and problem tasks with an inquiry and design or (re)construction based character was developed by the first author, who is experienced in course development. A teacher trainer colleague of the researcher reviewed the guidebook and suggested some improvements. Thereafter, two primary school teachers examined the guidebook in advance and also suggested some minor improvements. One experiment started two weeks before the other trajectories, which allowed for last-minute adjustments. However, modifications were not necessary.

The content of the guidebook was organised in four chapters following an assumed taxonomy with regard to the complexity of robotics concepts (function, system, control, SRA). A fifth chapter offered a comprehensive problem to be solved by designing and programming a (Lego Mindstorms) robot. The guidebook prompted the students to take notes when conducting the tasks. To be able to perform the tasks as a (re)construction students were provided with robotic materials, CD's with videos, pre-made programs for the Lego Mindstorms robot, et cetera. The student pairs worked on the tasks in the book. After finishing each chapter the teacher organised a reflective dialogue addressing the concept in focus in order to discuss and deepen the learning through discourse. In this experiment there was no possibility to prepare the teachers as thoroughly as described in the previous study (see chapter 5). Instead, we adjusted to the constraints teachers normally experience when they want to teach a new topic with which they are unfamiliar. We talked to teachers individually in a few after school sessions. We informed them about the important aspects of SMK, PK and PCK, using the same materials as in the teacher education course investigated in the previous study. Under these conditions there was little time for hands-on practical training sessions.

The experiment started January 2012 and ended July 2012, and was conducted in four primary schools, which were spread over the province of Limburg in the southeast of the Netherlands. Four teachers, not familiar with teaching robotics and who had not used Lego Mindstorms before, participated with on average twelve students from their own class. The teacher paired the students and in total 24 pairs of grade 6 students participated.

Data collection

Data were gathered in the form of answers and remarks from the guidebook, video or audio recordings of the reflective discourses, video/audio recording of a semi-structured interview with each teacher separately and with the group of participating students from each class.

Table 1.4: Study 4 overview research question, data collection and data analysis

Study 4	Research question	Data collection strategies	Data analysing strategies
	Why did the students not reach the intended level of understanding of robotics?		
		- 24 student pairs conducted the tasks of the guidebook and took notes from which students' answers and comments were retrieved, - 15 video recordings of reflective discourses between student pairs and the teacher, - remarks from the semi-structured interview with the teachers (4), and remarks from the interviews with the groups of students (4), - robotic programs produced by some of the students.	- The remarks and answers to the tasks in the guidebooks were clustered and quantified to interpret these against the background of the (conceptual) aims of the tasks. - Text fragments of the reflective dialogues, texts of teacher interviews and student interviews were open coded with MAXQDA.
	Identifying describing conjectures grounding and illustrating them.		- Constant Comparison Method and Two-step procedure of Cobb and Whitenack (1996) > Formulating conjectures from the condensed data set and testing these against the data set
	Understanding findings by formulating explaining conjectures grounding and illustrating them.		- Constant Comparison Method and Two-step procedure of Cobb and Whitenack (1996) > Looking for general patterns in the data set

Data analysis

In order to find answers to the central research question we used an approach in line with the Constant Comparison Method (Glaser & Strauss, 1967). We conducted a two-step data analysis procedure as described by Cobb and Whitenack (1996), to identify describing and explaining conjectures in order to empower or mitigate our assumptions. Step one was to obtain describing conjectures from the condensed dataset. Step two aimed at finding explanations for the conjectures found in step one. For this purpose, we looked for general patterns that could be turned into “causal mechanisms” (Maxwell, 2004) that might explain what happened.

In the first step we perused the condensed data set of the teacher-independent learning trajectory. This led to four conjectures that described students’ learning processes with respect to robotics and two conjectures concerning the reflective discourse. We tested these conjectures against the dataset through clustering and tagging the data in search of illustrating these characteristic examples (Glaser & Strauss, 1967).

To find establishment, refinement or rejection for the conjectures concerning the learning trajectory we analysed students’ remarks and answers to the tasks of the guidebooks. The first author clustered, totalised and evaluated these notifications with respect to students’ explicit understanding of the tasks and their approach of the task. The reactions were interpreted with respect to the aim of each task and against the underlying conceptual frame of reference. The four conjectures were found acceptable and slightly refined. With respect to the two conjectures about the teacher’s role and the reflective discourses we transcribed the video recordings of the reflective discourses and imported these texts in MAXQDA to be tagged. The transcripts of the teacher-students discourses were divided into episodes. An episode is a discrete section of the discourse that is internally related and can be discussed separately from previous or next sections. Utterances from such sections were interpreted with open coding in relation to the core subject of that episode. The labels that emerged referred to aspects of the dialogue and to aspects of the robotics concepts and sub-concepts in use. Depending on the specific concept in focus, different characteristics emerged from text blocks, sentences, or words. Elaborating on this we found supportive fragments in the data set for the conjectures concerning the reflective discourse. A teacher-colleague read the texts and checked the interpretations and in case of disagreement, the sections and coding were discussed and adjusted until there was sufficient agreement.

In the second step with the purpose to find explaining conjectures we analysed and discussed the findings in the research group. From these theory-building discussions three elucidating conjectures arose. These explaining conjectures were grounded in their argumentation power, by testing them against the whole data set and by illustrating them with characteristic examples (Glaser & Strauss, 1967).

1.3 Relevance of the research project

From a societal point of view the relevance of this research project is in its connection to prepare students for a technology-based society by providing them with the knowledge and skills one needs in a technological world. Conversely, modern society needs a strong science-, technology-, engineering-, and math- (STEM-) literate workforce (Nelson, 2012). Today, it is broadly accepted that education has to foster the development of students' technological literacy. Robotization is present everywhere in our world. It expands at a very fast pace and the possibilities of robotics often exceed our imagination (van Est & Kool, 2015). However, it is not easy to determine what we should teach students about robotics, nor how this could be done.

Therefore, it is important to invest in research on teaching robotics in primary education in order to equip students with relevant conceptual knowledge and skills. The theoretical value of this research project is in the expected additions to our knowledge about learning and teaching robotics in primary school. From a practical point of view the value of this dissertation is in the practical materials such as lesson plans, tasks and manuals that have been developed and used in the various studies.

1.4 Overview of the dissertation

This dissertation consists of one literature study and four empirical studies, which all contribute to the overarching research objective. The main goal of the studies in this dissertation is to contribute to a better understanding of how to teach robotics in a primary school trough using ICT-based robotic environments.

Chapter 1 is the current chapter and contains the general background, the problem statement and research questions, the relevance of the study, the context and participants, methodological considerations, and this overview.

Chapter 2 is the literature study in which is examined how the learning environment in primary education can be enhanced by the use of innovative ICT applications. The focus is on the notion of mind tools, which refers to (ICT) means that allow students to manipulate technology actively in such a manner that it helps them in developing knowledge and reasoning. The stimulating effect of mind tools in general and of specific sub-types with respect to the thinking skills and thinking attitudes of students is examined. Further the benefit of these tools is discussed.

Chapter 3 reports on the study 1 (described in the previous section) in which characteristics of students' thinking, when solving programming problems in a controllable micro world, were examined. Instruments and results are discussed and new assumptions and questions are put forward.

Chapter 4 describes study 2 (see previous section) in which was investigated what students can learn from working with a robotic mind tool in a one-to-two teaching experiment. The inductive data analyses in combination with a cognitive and conceptual analysis led to more specific understanding on what students learned about robotics. In relation to this, both the boundaries of the students' conceptual understanding, and teacher's role are discussed.

Chapter 5 is about study 3 (see previous section), which presents an investigation on how to prepare teachers for teaching robotics. A professional development course was developed and enacted. Various measures were used to investigate whether the teachers developed the intended SMK, PK, and PCK. The researchers' interpretations were checked with the participants.

Chapter 6 is on study 4 (see previous section) an investigation of a learning experiment in which students work through a teacher-independent course on robotics which is complemented with four reflective discourses with the participating students. The learning process was investigated. First the data were clustered, then a retrospective analysis was carried out in which we looked for patterns and for explanations of those patterns.

Chapter 7 summarises and reviews the main findings. Further, limitations of the study, directions for future research, and implications for practice are discussed.

The chapters 2, 3, 4 and 5 in this dissertation have been written as separate articles that have been published in academic media. Consequently, there is some overlap in the chapters. The studies were originally written in different language styles, hence, small differences in wording and minor mistakes in the text and the references have been corrected.

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Chapter 2: Mind tools contributing to an ICT-rich learning environment for technology education in primary schools*

Abstract

This study examines how the learning environment in primary education can be enhanced by stimulating the use of innovative ICT applications. In particular, this discussion focuses on mind tools as a means of leveraging ICT for the development of cognitive skills. The stimulating effect of mind tools on the thinking skills and thinking attitudes of students is examined. The various types of mind tools and a number of specific examples are closely examined. We consider how mind tools can contribute to the establishment of an ICT-rich learning environment within the domain of technology education in primary schools. We illustrate two specific applications of such mind tools and discuss how these contribute to the development of thinking skills.

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2.1 Introduction

We see that an ever-growing number of primary schools have all of the provisions in place for the fundamental use of ICT. They have enough hardware and software, they have a handle on the pedagogical organisation, and the teachers possess sufficient personal ICT proficiency. But that is not enough. Teachers often indicate that they still have too little knowledge regarding the pedagogical aspects of the advanced use of ICT. We add that this is supported by (Simons, 2002) who contends that there is still considerable expertise to be developed in the area of computer-related pedagogy. The challenge for the future is, therefore, to test and research applications of ICT in more open learning situations to achieve a richer learning experience. Educational programs for teachers should train participants to deploy ICT as a cognitive tool, also known as "mind tools" (van den Dool & Kirschner, 2003).

In modern educational approaches, students are to a greater degree responsible for their own learning and the teachers focus on the development of thinking (creative, logical, and critical), the students' search for and selection of information, and on individual and collaborative work situations. This sort of education provides room for students to actually participate and to enter into an active, constructive process with learning how to learn as the primary goal.

If we want to achieve all of the objectives mentioned above, we cannot limit ourselves to the creation of ICT-sober learning situations. Boekaerts and Simons (1993) observed that the simple courseware applied in these situations does not stimulate activity in minds, but rather in the computer. We see primary schools making reluctant attempts to implement applications that are consistent with an ICT-rich learning environment, often in the form of progressive ICT use within the current curriculum. In doing so, instructors encounter all sorts of unanswered questions. The lack of a well-formed pedagogical plan that can provide answers to these questions is a deficiency. It is, after all, the teachers' responsibility to seek the educational value of their efforts. With regard to the application of ICT this is no different. Certainly when the effects cannot be directly measured, a fundamental distrust for the introduction of ICT develops.

The more closely the application of ICT interfaces with existing educational practices, the more easily its effects can be measured. The danger in this, however, is that mainly ICT applications will be put into use in the most favourable of circumstances as nothing more than a substitute for what is already taking place. ICT as a replacement for routine tasks of the instructor is pedagogically and organisationally very clear. In this vein, we saw during the

1990s how relatively quickly drill-and-practice programs for mental arithmetic in primary education were adopted in addition to and as a replacement for rows of numbers on paper.

It is thus high time to search for a clarification of the added value of modern forms of ICT usage. This added value will hopefully translate into a transition or, better yet, even a transformation in education (de Wolf, 1998). In this paper, we will examine the value added by the application of modern ICT in schools. Through the use of examples we will demonstrate how these progressive ICT applications can deliver an appropriate pedagogical contribution to a relatively new field of interest in Dutch primary education, specifically in technology education, from which it will find its way in due course to other educational areas. Thereafter, we take a look at how specific applications of ICT and technology can function as "mind tools".

2.2 Mind tools, a first investigation

Mind tools are an aid that helps to stimulate critical thinking: tools for the cognition (Jonassen, 2000). With this statement, we make immediately clear that mind tools are not only computer applications. An electronics kit that contains many opportunities for experimentation and provides room to develop insight and knowledge can fulfil the same function as a computer program. Many modern computer applications are, however, well suited to serve the role of mind tools. Essentially, the learner uses the computer program in such a way that he or she creates a representation of what is being studied. Mind tools activate constructivist, higher-order, critical thinking. What is essential is that the learner interprets information and begins to organise his or her knowledge in a different manner. Mind tools provide assistance for reasoning related to content and provide possibilities for working with causal relationships and forms of analytical thinking. Students only begin using mind tools properly when they are encouraged to think critically about the subject matter they are studying.

Mind tools are not technical aids used to present subject matter that the student is consequently expected to reproduce. They are a means that allow the student to actively participate and manipulate the technology to increase self-knowledge and develop forms of reasoning. This development is not limited to the domain-specific knowledge that is contained in the technological resource; it also generates more generalised thinking skills and strategies.

This process of manipulation with a mind tool can occur in an individual situation, as well as in an interactive dialogue with others. According to the literature (ten Dam & Volman, 2002), the latter appears to deserve the preference.

Language appears to be an important factor in the construction of knowledge and the acquisition of insights (Wells, 2002). This language-based interaction must be goal oriented though, solving a problem together for instance, and be based on the development of new knowledge. According to this conception, based on what is called “progressive discourse” by Bereiter (1994), the various participants constantly provide suppositions, explore ideas, investigate the alternatives, and search for explanations or solutions that contribute towards progress in the solution of the problem. Learning through the manipulation of a mind tool is better supported when a language dialogue is possible with another learner. A student who puts his thoughts into words makes his thinking process explicit so that another can react to that process. This language-based interaction can take place by working together with the mind tool. The mind tool can also serve as an environment, in which knowledge is developed together, as is the case with “mind bridges” (San Chee, 1997), a multimedia environment specially designed to activate thinking processes.

In summary: mind tools do not make learning easier, but they do make it better. They compel the learner to manipulate knowledge more intensively and in greater depth. And that leads us to the question what exactly constitutes those cognitive manipulations.

2.2.1 Learning, mind tools, and habits of the mind

During the past decade we have seen that the ICT has had an enormous influence on research and society, a very strong reorientation of people’s conceptions of learning, the learner, and the role of the school. Kok (2003) describes a number of movements that have had an influence on theories about learning and teaching during the past century. What these movements have in common according to him is that children, of their own volition, can learn wherever an interaction with their surroundings is possible. It is, however, the richness of the surroundings that primarily determines what the child learns. This view is strongly supported by changing views on intelligence. There is much reason to believe that intelligence is not static but, rather, can be developed and trained (Costa & Kallick, 2002).

Applying mind tools to allow children to learn comes down to providing a (rich) environment, in which the student can construct knowledge and can reflect upon his interactions and thinking. The constructivist presumes that we develop mental models and adapt these to provide room for new experiences. This also indicates that learning implies the initiation of a thinking process; this is preferably a process that we share with others. A lot of research has been carried out on this sort of thinking process during recent decades. Jonassen (2000) employs the "integrated thinking model" of the Iowa department of education (Figure 2.1) to provide a description. This model is assembled from the following components:

- *content/basic thinking*, which has to do with the skills, attitudes, and dispositions required to acquire accepted knowledge
- *critical thinking (analysing)*, which is defined as the dynamic reorganisation of knowledge in a meaningful and usable manner
- *creative thinking (synthesising)*, which includes surpassing the accepted knowledge to generate new knowledge
- *complex thinking*, which originates when the basic components content thinking, critical thinking, and creative thinking that is the accepted, the reorganised, and the generated knowledge, are deliberately integrated to achieve a specific goal.

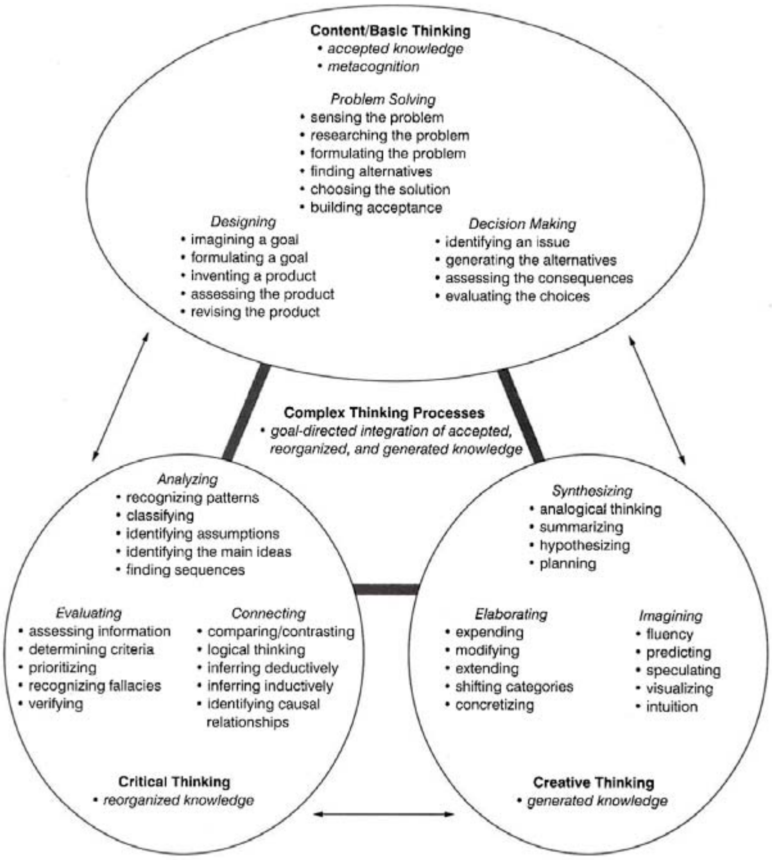

Figure 2.1: Integrated thinking model (after Jonassen, 2000)

Teachers search continually within the limits of the current curriculum for opportunities to teach children thinking skills. The contemporary education methods, through their nature and use, hardly lead to processes of critical or creative thinking, let alone to the complex thinking skills of the integrated thinking model. In many methods, learning is guided through the distribution of information and assignments. Seldom is the starting point of learning sought in challenging, activating situations that appeal to the attention and interests of students, for example, the problem solving, designing, or decision making situations that the integrated thinking model describes under "content/basic thinking". These complex thinking processes are based on the goal-directed integration of accepted, reorganised, and generated knowledge (Figure 2.1). When the teaching of underlying thinking skills occurs in isolation, one does not develop the habit of applying these skills to new situations.

For this purpose, Costa and Kallick (2002) define the concept of a "habit of mind". It consists of skills, attitudes, cues, past experiences, and proclivities. In their view, intellectual behaviour is always based on combinations of choices determined by the situation, which lead to a certain intellectual pattern. It is, therefore, necessary to expose students to a demanding intellectual environment for an extended period of time. In such surroundings, attention can be given to the teaching of habits to the mind. Altogether, this demands a fundamentally different perspective on the role of "presented" education. Education should lead to children's development of cognitive strategies by constantly compelling them to formulate questions, face challenges, seek solutions, explain concepts, answer questions, substantiate reasoning, and retrieve information. The "generative science teaching" approach formulated by Wittrock (1994) with its emphasis on productive learning processes, fosters this kind of education. Wittrock lets students revise their own models and concepts on the basis of active learning endeavours. These endeavours confront students with the scope and (im)possibilities of their own model. By setting goals that cannot be achieved too quickly but which do result in gradual, visible progress, the students are continually motivated to reformulate their perceptions. This results in more profound learning.

Costa (2002) describes the following 16 habits of mind:

- persisting
- managing impulsivity
- listening with understanding and empathy
- thinking flexibly
- thinking about thinking (metacognition)

- striving for accuracy
- questioning and posing problems
- applying past knowledge to new situations
- thinking and communicating with clarity and precision
- gathering data through all senses
- creating, imagining, innovating
- responding with wonderment and awe
- taking responsible risks
- finding humour
- thinking interdependently
- remaining open to continuous learning.

While the Iowa model involves the integration of a number of fundamental thinking skills, Costa seeks the expression of characteristic behaviours that are conditioned to allow the thinking skills to be optimally utilised. If the educational system wishes to achieve the correct application of thinking skills, it is inevitable that a fundamentally new philosophy will have to guide the manner in which the available educational instruments are employed. That philosophy begins with the stimulation of the sort of behaviour that Costa describes, with its attempts to initiate in students the complex forms of thinking that develop from an accepted knowledge base and from considering information critically and creatively. As mentioned earlier, the fundamental idea is that intelligence is not static but that it can grow. Mind tools are the sort of tools that stimulate such growth.

From our first explorative experiments with the use of mind tools in education, we received signals that students were learning in a different manner. A detailed description of what and how they learn is not yet available. Our observations, however, dovetail with the supposition of (Jonassen, Howland, Moore, & Marra, 2003) that mind tools make learning more meaningful. These authors claim that the implementation of mind tools contributes to learning based on the characteristics of meaningful learning; in this case that amounts to

- active (manipulative/observational) learning
- constructive (articulate/reflective) learning
- intentional (reflective/regulative) learning
- authentic (complex/contextual) learning
- cooperative (collaborative/conversational) learning.

2.3 Mind tools further classified

Before delving into the manner in which mind tools can be used in education, by way of setting the stage, we discuss some categories of mind tools according to Jonassen, Carr, and Hsiu-Ping (1998) and provide some examples.

2.3.1 Semantic organisation tools

Semantic organisation tools help the learner to analyse and organise semantic, meaningful information. The two most familiar applications are database programs and various tools for building semantic networks.

Both during the construction and structuring of a database, as well as during its use, the user must ask himself questions: What do I want to use it for? For what type of questions should the contents provide answers? How must I phrase the questions to access the knowledge? How can I use the fields and which fields should I use?

Semantic networks provide a representation (often visual) of meaningful interrelationships between concepts. Through the use of symbols, a conceptual network is built around an idea – the time-honoured “word web”. The nature of the relationships and the form, which they are given are determined by the learner. Through structuring and restructuring, the learner actively builds a

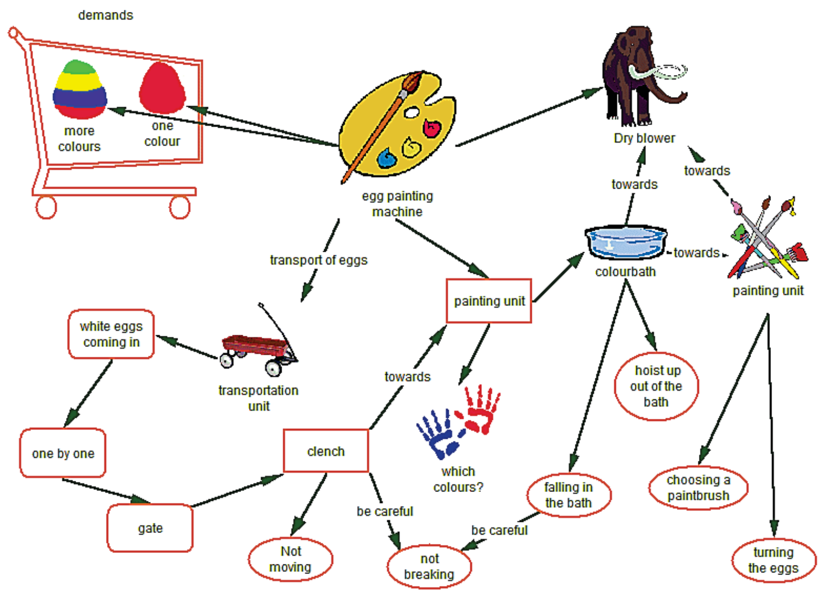

Figure 2.2: Mind map designed with ‘Kidspiration’

personal knowledge domain and learns to analyse, describe, and see past the relationships. See Figure 2.2 for an example.

2.3.2 Dynamic modelling tools

Dynamic modelling tools help the learner to describe, manipulate, and expand upon the dynamic relationships among ideas. This category includes various tools that make dynamic mathematical models accessible for non-mathematicians. Nevertheless, models of this type very quickly become quite complex (see, for example, Doucet and Sloep (1992)). The simplest examples are spreadsheets and, particularly, the so-called micro worlds.

Building a model of reality in mathematical terms requires a large measure of abstract reasoning and is closely related to mathematical and logical thinking. The strength of models in this category is that they offer more than a calculator because they make the relationships between the variables visible. This is also true for spreadsheets. This type of models lets the user ponder how a problem can best be approached and how a series of decisions can best be structured.

Micro worlds are small (partial) virtual worlds in which the learner can navigate, make decisions, experience consequences, expand ideas, and so forth. Often they are limited simulations of real world situations. Micro worlds are possibly the most pregnant example of active learning environments. They are very popular with young people. Many of these worlds are derived from a basis in mathematics, physics, technology, or information science. Two well-known examples are SimCity and Logo.

Krumholtz and Markuze-Haas (1998) and Krumholtz (1998) describe the micro world “Techno-Logic” that is especially suitable for use in primary

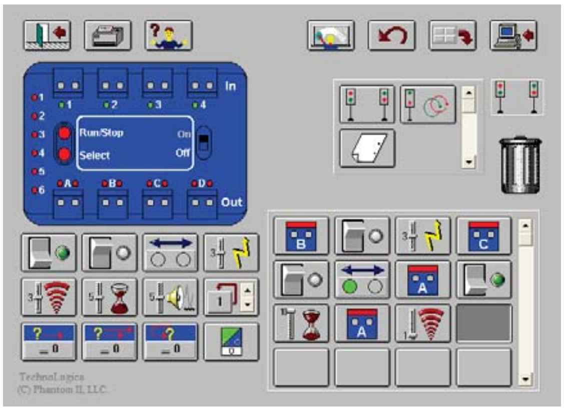

Figure 2.3: Screen capture of the Techno-Logica control software for the interface Leonardo

education. It is a physical (external) micro world, for example, a toy consisting of a collection of electromechanical components (construction material with motors and sensors) that is controlled by a computer. Techno-Logic integrates creative construction of physical machines and models with a computer-based process controller that is made accessible through an interface. In this micro world, children can examine and experiment with physics concepts and their applications in technology. Techno-Logic is a mind tool that offers many opportunities to provide practice in problem solving and to aid in the development of thinking skills and habits of the mind. Figure 2.3 shows a screen capture of the Techno-Logica control software for this micro world.

2.3.3 Information interpretation tools

Information interpretation tools help make information more accessible for learners and assist them in processing that information. This category includes search engines, hypermedia, and weblogs (blogs).

Search engines offer the learner a chance to gather information in a systematic and logical manner. The process of determining the correct search parameters through a series of refinements is well suited to the assimilation of thinking skills.

Hypermedia consists of information links that serve to make information stored in any form (video, text, image) accessible. A user can add or change information to create links. In its entirety, it becomes a dynamic knowledge base. The idea that making this sort of (instructional) material teaches more than using it is supported by ThinkQuest, where children can make their own websites. This is, by the way, one of the most common examples of the use of mind tools in the Netherlands. The idea that it is not the website (the product) but rather that the creator learns during the development, construction, and content creation of an educational website (the process) is, unfortunately, often contended. We observe that in daily practice the website (the product) is mostly seen as the goal instead of as a means of learning (the process), or we see that mastering the tools (software used to make websites) is seen as the ultimate learning goal.

Blogs are a special sort of webpage intended for (restricted) public use (Poortman & Sloep, 2005). A diary format is typical. Mostly the contents include short, regularly updated messages in inverse chronological order. These pages can include all sorts of things, such as links, information blocks, diary entries, photos, project updates, and so on. Some blogs are personal, and others are the result of collaborative work. With special tools, blogs can be given extra functionality. They are interesting in the framework of managing dynamic information, but in addition they also serve a clear communicative function.

2.3.4 Conversation tools

Conversation tools are appropriate for learning through discussion. They make use of communication techniques that are useful for negotiation, careful consideration of contributions, synthesis, and inclusive and exclusive thought. Examples of this type of application are instant messaging, email, forums or discussion boards, and once again blogs (assuming they are supplemented with support for threaded discussions among visitors).

Instant messaging is a synchronous conferencing application. The number of participants is theoretically unlimited, although there is a practical limit of approximately five per session. Properly used, this resource can be used to teach, argument, and reasoning. At present, this application is used very intensively by young people, primarily for private communication. Specifically, because of the synchronous nature of the communication there is little time for extensive deliberation. The participant is thus compelled to think and react quickly.

E-mail and discussion boards are asynchronous means of communication. Like instant messaging they offer a forum for argumentation and reasoning, but in contrast these tools emphasise careful consideration and formulation.

2.4 Introducing mind tools to primary education in The Netherlands with technology as platform

Although the desire that more attention be directed towards the learning processes, the learning of thinking skills (van der Meer & Nuyens, 2002), cooperative learning, and constructivist learning is repeatedly heard within the Dutch education community, we see that ICT applications that could make this possible are only sporadically employed in daily teaching practices. Too little concept of the practical interpretation of such an ICT-rich learning environment, unfamiliarity with the possibilities, and the added value of such an approach, as well as inexperience with the application of ICT are probably to blame. It requires an unconventional approach from teachers to implement such instruments, and within the prevailing educational situation there are but few incentives to follow this path. We are not, incidentally, dealing with innovation in the area of educational equipment any more. We have already established after all that both the facilities, as well as training in the use of ICT are at or above the required levels. ICT-rich learning environments require more. They presume an optimal balance between learning and teaching, a constructivist vision of that balance, and once again an appropriate pedagogical approach from the instructor. The domain encompassed by technology education can serve as a suitable platform.

Technology as a content area for achieving educational goals has long been out of fashion in Dutch primary education. In recent years, it has become a focus in the educational reforms of primary education. The explicit attention for this domain of learning provides a plethora of chances to redirect the orientation of those providing instruction from traditional ICT use towards new applications of ICT. For the students, this means that they can make use of advanced technological tools that allow them to go beyond the borders of classical learning tools and methods. Virtual worlds created by mind tools make the unknown conceivable and visible, and allow it to be manipulated. In this way, these tools support in particular the need of young students to have abstract ideas demonstrated through concrete examples to aid in their understanding.

Just as with insights about modern ICT usage, the recent notions about responsible technology education are primarily fed by educational concepts associated with the "new learning", such as constructivism, brain-based learning and multiple intelligence, cooperative learning and learning styles (Slangen, 2005). The teaching of technology employs to this end such key concepts as problem solving, (re)design, producing, researching, analysing, evaluating, and reflecting, in which both the product and the learning process are equally important. Mind tools can serve well as learning tools for the development of (technical) thinking skills. Then again, mind tools as instruments (software) are themselves the result of modern technology.

Teachers are not only expected to carry out the established educational plan, they are also expected to function as developer of learning environments and improver of education (Wubbels, 2002). For pre-service teachers, it is therefore, clear that they will come into contact with this aspect of the profession. Schools focus more and more attention on the development of educational programs that are directed towards knowledge development and the coupling of theory and practice; in these the pre-service teacher is both researcher and developer of education. In this framework, pre-service teachers with a specialisation in technology and ICT can serve as catalysts for the implementation of new applications in these areas during their internships.

2.5 A further look at several mind tools

With the expectation that various mind tools contribute to the development of the (technical) thinking abilities of children, these have been implemented during the internship period of pre-service teachers to develop an ICT-rich learning environment for technology. We illustrate, with two concrete examples, how mind tools contribute to technical thinking skills.

2.5.1 Kidspiration

Skills that are important within the content domain of technology involve learning to solve technical problems and learning to design based on these solutions. Development skills and problem solving skills are called upon in a continuous cycle. In the beginning phase of development, processes are based on many different thinking skills, but these tend to be concentrated in the creative range. Later, thinking skills of a more critical nature are needed. Developing a good design often demands, at the start, both free association and departure from established thinking. Creating the design requires (re)organisation of information into new, meaningful arrangements and entities. Additionally, it involves analysis, (re)grouping and organisation according to various criteria, further refinement of parts of the design, and so forth.

The development of new technology or the redesign of existing technology entails the use of known data, generation of new information, and the reorganisation of data and information. It involves, in other words, a continual process of semantic organisation. Explicit external representations, such as concept maps, to support association and conceptualisation lead to the formation of new ideas – in other words, to learning (Kommers, 2004; Lavik & Nordeng, 2004). Specifically, graphical representation offers the brain significant support for the application of semantic organisation and the development of thinking. According to (Buzan, 1991), activating the entire brain requires not only words, numbers, structures, sequences, and lines, but also colour, figures, dimensions, symbols, and visual rhythms that is, mind maps. Mind maps are representations of semantic concepts. Modern mind mapping software is, therefore, considered to be one of the most powerful instruments for semantic organisation and the active and efficient creation and manipulation of representations. Mind mapping software can, for this reason, be widely deployed in education, in every situation that involves the generation of ideas.

Kidspiration falls under the umbrella of semantic organisation mind tools and is primarily suitable to assist young children in brainstorming, after which the output can be organised in more systematic diagrams that can be further used to create development and planning diagrams. It assists in the learning of thinking, writing, and understanding through the creation of diagrams with illustrations, text, symbols, and spoken words. In this process, they make their ideas visible and show the interrelationships. Within the graphical display children build, for example, groups, word webs, association diagrams, or conceptual maps. Thereafter, they carry their work over to a notebook where their ideas can be further refined in words, leading to crystallisation of the design.

Figure 2.2 shows the results of a first brainstorm, within the domain of technology, for the development of an egg painting machine. After this first round of creative thinking, more organised and refined actions must be applied to the mind map.

2.5.2 The Techno-Logic micro world as mind tool

Techno-Logic can be described as a mind tool with which children learn physics concepts and can explore and apply their technological applications. Techno-Logic offers possibilities, in the right educational setting, to transition from learning problem solving to the development of thinking skills and habits. Characteristic of this micro world is that it is manifested in the physical world, but studied through a computer. In a problem solving educational setting, the Techno-Logic world invites active manipulation, in which feedback through testing of the model, statement of hypotheses, analysis of the problem, and the search for causal relationships continually stimulate critical thinking processes (Figure 2.4).

Figure 2.4: Programming Techno-Logica software and the interface Leonardo in a school project 'the fair'

Techno-Logica is the software with which a working model of some machine is controlled. Its most prominent part is the interface “Leonardo”. It has four ports that control devices such as motors or lamps. There are also four inputs for the connection of various types of sensors (temperature sensor, magnetic sensor, etc.) that can provide feedback on the basis of which the computer can make decisions, carry out actions, and so forth. For example: Stop the car of the Ferris wheel for five seconds, rotate the wheel to the following car, and so on. Once all of the cars have passed, the start signal is activated for three seconds, the lamps begin to flash quickly, and the wheel begins to turn. The development of a control procedure in the computer program occurs through the placement of various action buttons, sensors, ports, and decision junctions in a specific order. In addition, buttons can be created that contain procedures. We see here strong similarities to the programming language Logo (Papert, 1980). The program is developed in such a way that it does not require much programming knowledge but rather initiates a thinking process.

Writing such a control procedure requires a large measure of logical, critical, and creative thinking from children. On the basis of practical experiments in primary schools, we ascertain that this sort of technical activities calls greatly upon thinking skills (causal relationship concepts, comprehension of parallel and serial processes, recognition of faulty assumptions, deductive reasoning, etc.). Habits of the mind are just as rigorously exercised (flexible thinking, accurate thinking, being persistent, gathering data and using what you already know, and so forth). The development of complex control processes is an activity that places strong demands on critical, logical, and creative thinking. Based on his or her choices, the user can test the application, analyse the consequences, and try new procedures. The concrete nature of the response (something occurs in the physical model) makes it very easy for primary school children to gain insight into the application of the computer procedures. By applying them, after all, you see whether or not it works and whether you have properly thought things through. With small changes you can test and improve your thinking.

Our first experimental explorations into the possibilities for employing the mind tool Techno-Logic support the assumption that children actively engaged in dialogic interactions are intensively developing thinking skills and thinking attitudes. These observations are supported through experiences with this mind tool elsewhere (Krumholtz, 1998), in which it appears that children develop some form of technological thinking (technical concepts, research skills, and problem solving skills in a technical context).

2.6 Conclusion

Changes in education are not enacted through the implementation of new media alone (Westera & Sloep, 2001). And if the implementation of new media leads to changes, they do not take root or they do not have the desired effect (Oppenheimer, 2003). The starting point for every transition or transformation in education is a change in teacher behaviour. But we must also implement a number of strategies in education to adopt new premises about thinking, learning, instruction, progression, and teaching. This requires rich learning environments for active learning (Grabinger, 1996). (Bereiter, 2002) speaks in this context about “progressive education”. We can expand on this by saying that there is a need in the day-to-day educational practice for concrete instruments that provide a practical way of putting these progressive ideas about learning and teaching into effect. The fundamental observations about this different approach to learning and teaching are certainly not new. The manner of achieving these goals, however, in recent years has gained more support through societal and educational shifts. Mind tools are among the instruments that can contribute significantly to that new educational system. Sometimes they are a generalised educational application (mind map software), and sometimes they are more specifically developed for a particular domain, for example, technology (control software for technical applications). However, in both instances they achieve two goals:

- they help to create the desired rich learning environment that involves students in active learning
- they allow instructors to gain experience with the applications and effects of constructivist learning.

Thus, mind tools support the creation of an educational learning situation focused on the development of general thinking skills and thinking attitudes.

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Chapter 3: A case study about supporting the development of thinking by means of ICT and concretisation tools*

Abstract

Improving learning and thinking in school has been an objective of the educational community for a long time. Computer applications and especially mind tools can be helpful in reaching this objective. Control software that operates a connected physical micro world and is used as a kind of mind tool, delivers possibilities to develop and support learning and thinking of students in school. We studied students' thinking behaviour (thinking skills and habits of mind) by analysing the progressive discourse of students who solved problems using Techno-Logica control software in a hybrid micro world. We developed a first version of an observation instrument and tested its usefulness in exploring thinking behaviour. In this chapter, we present the first results and prospective.

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3.1 Introduction

According to (Bereiter, 2002), human cultures have arrived in the era of knowledge societies and knowledge economies. Therefore, we need new theories on learning, teaching and knowledge. In order to produce new expertise one needs to elaborate skills to acquire and process information. More and deeper understanding of the use of complex thinking processes (both critical and creative ones) is needed in order to build curricular lines congruent to subject matter domains, across mental skill repertoires and personality traits.

ICT offers many chances to find innovative ways of teaching and supporting cognitive development of learners. Kommers (2005) asserts that the continuous stream of new media and ICT applications is the main source for the evolution of education. Developing cognitive learning tools that instigate new pedagogical values; this is the challenge for the next coming years.

This study emphasises the importance of stimulating active learners in solving meaningful problems by means of ICT applications. The notion of mind tools seems to be crucial for studying modern ICT applications in innovative pedagogical contexts. Mind tools are the overarching class of learning support software that aims at activating (generic) learning and thinking skills (Jonassen, 2000; Jonassen, Howland, Moore, & Marra, 2003). It also aims at articulating learning attitudes and habits of the learner's mind (Costa, 2000).

A good teacher should not only manifest competences like instructing and testing students' knowledge. Good teachers offer the students various opportunities to learn (collaboratively) by using gifts of modern technology. In spite of that, we know that ICT in its innovative sense is not easily adopted by teachers. Pre-service teachers could well have an important role by the adoption and implementing of these new technologies (Bers, Ponte, Juelich, Viera, & Schenker, 2002; Slangen & Sloep, 2005). They are more accustomed to modern technologies and, as we experienced, they adopt the employ of ICT as a new educational technology more easily.

In this chapter, a case study is described in which a pre-service teacher used control software based on a concrete micro world to stimulate collaborative learning and thinking processes at the primary level with students of 11 and 12 years old. A Techno-Logica problem solving task was offered to initiate discourse and active thinking behaviour. We developed an observation tool to collect data and gain more insights into thinking behaviour. Initially, we describe the position of learning and thinking in school and the role of mind tools, after that we analyse some previous research on the use of control software and concrete tools. Subsequently, we explain our case study and end up by presenting some preliminary results and conclusions.

3.2 Mind and tools in school

Learning and thinking are innate and intertwined qualities of a human being. People learn a lot spontaneously. However, sometimes learning and thinking are explicitly organised, e.g. in schools.

3.2.1 Learning: the role of schools

The challenging question is: does learning really need schools? In any case, it may be claimed that schools pretend to optimise the efficiency of learning.

Resnick (1987) asserted that schools aim at the development of higher-order thinking skills such as critical thinking, problem solving, reasoning, refining ideas, interpreting and creative applying of these skills. In addition, as we have stated that such skills are important tools in modern society. Schools should choose strategies that activate thinking processes leading to a rich knowledge base, form concepts and understanding, and strengthen the thinking behaviour in itself. However, many schools are not very successful in reaching these goals (Boostrom, 2005; Resnick, 1987). Despite the emphasis on the importance of the process of learning and thinking, many teachers still practice the teaching as a process of conveying factual knowledge in itself. Teachers expect the learner to accumulate and absorb knowledge.

Study of experts' knowledge demonstrates the importance of the combination of having a large knowledge base of facts at one's disposal and having it associated and organised around important concepts (Bereiter, 2002; Bransford, Brown, & Cocking, 2004). We conclude that learning is more than gaining and reproducing declarative or procedural knowledge. It is the development of connected concepts and insights by using this (factual) knowledge. Learning can only be successful if it makes sense. An emphasis should be placed on learning with understanding. Schools should organise learning in such a manner that real understanding can develop.

Concrete learning could be very helpful in developing the better comprehension of fundamental insights. Children do often gain sudden understanding after visualising (concretising) abstract processes or problems. The benefit of learning by using real-world objects and/or context is often underestimated. For that reason, concrete learning should get more attention, but not only as a stepping stone towards abstract learning (Papert, 1993).

Concrete learning should also have a powerful intrinsic value. (Bereiter, 2002, p. 120) says:

> *"Understanding the problem may require understanding other abstract objects, but also requires some engagement with the real world phenomena that give rise to the theoretical problem. It is the same as with understanding a tool or a machine."*

Papert (1993) advises that teaching practice should change structurally. Schools should use the power of natural learning by favouring constructionism over instructionism. From a social constructivist perspective learning is a process of personal development through constructing and reconstructing new and previously acquired knowledge in interaction with the other. Such processes can be initiated and mediated by using concrete learning objects and tools. Therefore, teachers should use these objects and tools to organise constructive learning experiences in school. By doing this, teachers have many opportunities to stimulate conscious and reflective learning. That is the main reason for the existence of schools.

3.2.2 A focus on activating thinking in schools

For many centuries, philosophers, psychologists and educationalists have been trying to map out processes and tenets of thinking by studying these very accurately and describing them in manageable terms (Bransford et al., 2004). The gained insights should help the teacher realise that education should stimulate learners to think more effectively. The question is whether a classifying system of thinking behaviour should be converted to prescriptive teaching rules? This question already suggests that different categories of thinking behaviour can be converted into teaching modes. "A taxonomy can be invented to classify instances of thinking after they have occurred, but it cannot show us how to create these instances" (Boostrom, 2005, p. 25). Resnick (1987) signals that thinking is teachable, but that there is no evidence that higher-order thinking can be learned by acquiring specific components. This means that teachers' objectives should trigger thinking by continuously using appropriate activities rather than teaching thinking in isolated tasks. If we want to activate higher-order thinking that is more than memorising, students can only be activated in this way by confronting them with materials, situations or contexts they have never dealt with before (Boostrom, 2005). Based on theories of the neurobiology and brain-based learning, Kok (2003) described some implications for creating valuable learning environments. These environments should arouse realistic and holistic learning experiences in which students can be entirely wrapped-up. This implies offering complex tasks that stimulate a lot of thinking and that have a high degree of safety, challenge and active involvement.

We suppose that thinking is improvable. However, the question remains if we can identify generic thinking skills or if thinking skills are based on content and context. In other words, is thinking based on different skills or is it based on various kinds of dispositions? Experts are not just "general problem solvers", they seem to solve problems by using a base of well-organised knowledge (Bransford et al., 2004) and strategies. Experts do not only recognise easier relevant aspects of problems in new domains they also choose different starting points and ways of tackling problems than novices. We conclude that it is a fact that thinking needs context. Various contexts are needed for eliciting realistic prior knowledge. As (Resnick, 1987, p. 45) says: "Good thinking depends on specific knowledge, but many aspects of powerful thinking are shared across disciplines and situations". Facts or (organising) notions and former learned skills make it easier for an expert to think in specific situations in a more sophisticated manner.

Costa and Kallick (2000) described the relationship between thinking skills and habits of mind in a model composed of four concentric circles (Figure 3.1). In the centre circle, we see discrete thinking skills, such as comparing, classifying, recalling and etcetera. Nevertheless, these skills operate only

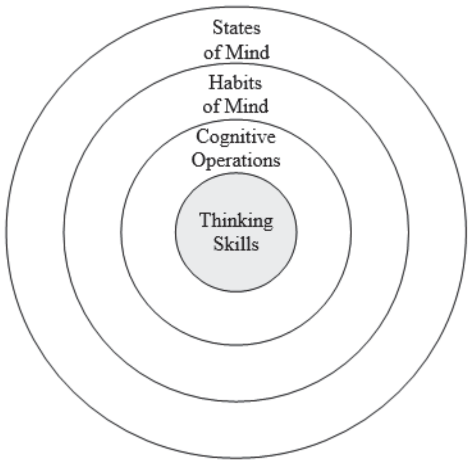

Figure 3.1: Circles of relationship (after Costa & Kallick, 2000) relation model of thinking skills, cognitive operations (higher order thinking skills), Habits of Mind, and States of Mind

within cognitive operations (the second circle) which are larger and more complex strategies, such as problem solving and decision-making. The third circle that encompasses the previous two contains the habits of mind, which are characteristics of intelligently acting. The fourth circle contains states of mind, such as motivation, balance, and drives. The integrated thinking model (Iowa Department of Education, 1989) offers a more detailed picture of the relevant components of these two inner circles (thinking skills and cognitive operations). Cognitive operations (complex thinking processes) such as problem-solving, designing and decision-making, need on their turn thinking skills, like critical thinking (analysing, evaluating, and connecting), creative thinking (synthesising, elaborating, and imagining). Higher-order thinking skills such as critical thinking and creative thinking in succession relate to reorganising and generating knowledge. This higher-order thinking needs content/basic thinking (accepted knowledge and meta-cognition). Content thinking concerns facts, rules, skills, concepts, principles of the specific domain, etc. Basic thinking relates to simple learning to learn skills. Both approaches have in common the assumption that intelligent thinking is not a collection of separate skills but a complex interactive system.

The integrated thinking model (Iowa Department of Education, 1989; Slangen & Sloep, 2005) was composed to support educators in their work on developing curriculum and instruction. Teachers should use more opportunities (tools) to offer students complex and holistic tasks, to arouse and sustain their active thinking behaviour, keeping in mind the underlying components. We state that modern ICT-tools are well suited for this purpose. ICT-tools, like the ones we mention further on, are useful to generate motivating problem-solving and decision-making tasks in which learners can act intelligently, activate complex thinking processes and use skills such as critical and creative thinking. They function as teaching tools that empower thinking.

3.2.3 Mind tools support thinking activities

It is the student, him or herself who learns or thinks and it is the school that should offer opportunities for good learning and thinking. Therefore, teachers, computers or books are just devices to activate or support these processes. (Jonassen, 2000, p 4) defines mind tools as "computer applications that require students to think in meaningful ways in order to use the application to represent what they know". This indicates that not all computer applications or the use of these applications can be seen as mind tools. Such applications should at least trigger meaningful learning activities which can be defined as: active (manipulative/observant), constructive (articulative/reflective), intentional (reflective/regulatory), authentic (complex/contextualised) and cooperative (collaborative/conversational) (Jonassen et al., 2003).

The last decade has shown a fast evolution in the development of ICT applications concerning the so-called micro worlds. Micro worlds are usually defined as software environments for creating virtual worlds in which objects and/or virtual actors can be controlled and/or programmed (incredible machine, Sims city and second life). In such worlds, a learner can navigate, make decisions, experience consequences and expand ideas. Often, micro worlds are limited simulations of real world situations. They are powerful mind tools that portray the dynamic relations of the content, and can be used to construct simulations or virtual models. All micro worlds have in common that they take the learner to a constraint (safe) environment where new constructions can be made while the system provides feedback to the learner.

We can also identify other kinds of micro worlds. The hybrid ones that combine control software with a real physical play world like Lego, Fisher Technics, Lazy, etc. Software applications like Techno-Logica and Lego Mindstorms are both control software applications that operate objects in a physical world (Figure 3.2). These software applications can be used as mind tools, which, from a constructionist point of view, activate higher-order thinking of students.

Figure 3.2: A pair using Techno-Logica software to control the traffic lights and solve the problem of the road narrowing

Nevertheless, we should be warned. Bereiter (2002, p. 381) supposes that: “if the only justification for an activity is that it is supposed to encourage or improve thinking, you should drop it and replace it with an activity that advances students’ understanding or that increases their mastery of a useful tool”. Mind tools, therefore, should be applied in a context that is worth in itself to learn from, about or with. The context, in which we situate the use of these hybrid micro worlds, is related to learning from content and concepts out of physics, technology and science. These contexts are motivating and offer the learner many opportunities to develop situated knowledge of the specific domain. However, if we really want to support curriculum and instruction with useful mind tools we have to know more about the characteristics and the contribution to teaching and learning of different kind of tools and tasks.

3.3 Research on micro worlds and concretisation tools

Lego Mindstorms, Techno-Logica and Empirica Control are all examples in which concretisation tools (concrete physical models) are controlled by means of icon-based control software. Lavonen, Meisalo, and Lattu (2001) suppose that a visual programming tool based on icons is easier to be learned than a programming language based on text. The tools can be used in a more effective way, e.g. for learning concepts of physics. Learning a programming language is not the goal in itself.

We suppose that software that control concrete physical objects or models have some special features, which are very useful in learning. First, these tools stimulate students’ active thinking through using the concrete context of a technologic and scientific world. Secondly, they give rise to an increasing understanding of scientific and technological concepts and to logical thinking within these contexts. Thirdly, as our study showed, many opportunities are offered to provide practice in problem solving and generic thinking skills.

Krumholtz (1998), who uses Techno-Logic software in combination with technological construction material, found an increasing intuitive and formal understanding of concepts from physics, e.g. speed, acceleration, gravity, friction, force and balance. In various studies, the use of Lego Mindstorms has been supported. Bers et al. (2002) show us how Lego Mindstorms encourages the development of pre-service teachers’ technical fluency and how it is used to teach young children (Pre-K to 2) difficult concepts, e.g. that of a life-cycle. This way of handling Lego Mindstorms shows how its use is based on the four tenets of constructionism: learning by design, manipulating objects to think with, exploration of powerful ideas and self-reflection. Savage, Sánchez, O'Donnell, and Tagney (2003) describe a Problem Based Learning (PBL) experience in robotics with non-technical third level students. The conclusion of this study was that the combination of constructionism, mind tools and discourse offers a great potential to promote higher-order thinking skills. We also noticed other promising experiences of cognitive, emotional and social learning of students and teachers in primary schools and schools for special education through constructing robots and programming them with Lego Mindstorms (Eronen, Sutinen, Vesisenaho, & Virnes, 2002; Kärnä-Lin, Pihlainen-Bednarik, Sutinen, & Virnes, 2006; Sutinen, Virmajoki-Tyrväinen, & Virnes, 2005).

Nevertheless, several results are less positive. Lavonen et al. (2001) studied 14 years old students in a learning environment based on physical hardware and the programming tool Empirica Control to solve open ended problems. No formal learning caused by the programming tool could be found. The teacher had only a questioning role. The students showed almost no systematic planning, reflective and creative thinking, and they often used trial and error strategies. Even when a programming tool is icon-based, it seems necessary to learn some basics before, and not during, the problem task performance. (Lindh & Holgersson, 2007) investigated the effects of Lego training on students' performance on mathematics and technical tasks. The results showed an unclear picture of the contribution of Lego training in students' capability solving logical problems. There was no (statistical) evidence that the average group performed better, but there was some evidence that subgroups of medium good students did profit of the Lego training tasks.

Hence, the assumption that the combination of constructionism, mind tools and discourse offers a great potential to promote higher-order thinking skills still asks for further research. In this study, we present some first results of a case in which Techno-Logica is used as a tool to activate intense higher-order thinking behaviour.

3.4 Techno-Logica as an educational tool to think with

Making teachers more sensitive to use hybrid micro worlds as a learning tool demands the breaking down of at least three barriers. First, teachers themselves should be convinced that these tools support the development of technical insights and the thinking of learners. Secondly, teachers should become more experienced and self-confident in using micro worlds fluently (Bers et al., 2002).

Thirdly, the tool should easily fit in the actual educational system. Therefore, we explored the following questions:

1. Is Techno-Logica a useful mind tool to construct teacher independent and PBL?
2. Can we observe active higher-order thinking and habits of mind in such a learning environment?
3. If so, which types of higher-order thinking and habits of mind do we notice?

3.4.1 Techno-Logica as a concretisation tool

Techno-Logica controls an external and concrete micro world, e.g. an electromechanical toy consisting of a collection of components by a computer (e.g. construction materials such as Lego-Technic, Fisher-Technic, Lazy, K'nex with motors and sensors). Techno-Logica integrates the construction of physical models with a computer-based process controller that is made accessible through icon-oriented software and an interface. In this hybrid micro world, children can examine and experiment with physical and science concepts and their applications in technology. By using the control software, the concrete models can be programmed and controlled and a testing session gives immediate feedback. The software contains four levels of complexity: direct, automatic, interactive and collaborating mode.

3.4.2 The design of the children's learning space

Based on the theoretical views of learning and thinking, our concrete experiences with these hybrid micro worlds and the research questions, we decided to design a learning space with the following six conditions:

1. The learning space exists of a concrete and a virtual world, which are interdependent and connected.
2. The problem space is limited to solving a problem in one world (virtual or real) at once.
3. A challenging problem that stimulates the learner to manipulate the objects is presented.
4. The material is teacher independent and a teacher can easily coach the students who use it.
5. The material is easy to learn and handle for teachers.
6. The effected learning is social-constructivist in nature.

We used an instruction booklet, the interface Leonardo, physical objects (bulbs, motors, ground plan of a road narrowing, traffic lights and a Ferris wheel) and a computer with the software. The material is completely self-instructing. Using the booklet, a pair successively learns three levels of the programming tool. After finishing the learning of level two (automatic mode) and three (interactive mode) the students get a pre-defined problem to solve. The role of the teacher is only (when necessary) to pose indirect questions. At level two, the problem to solve is designing a well-functioning programme to control the traffic lights of the road narrowing. At this level, students use the automatic mode to programme four output ports (bulbs) in the correct sequence. The problem of the Ferris wheel is based on some pre-described actions that should be performed. For example, "let the Ferris wheel turn around five times left while the bulbs flash slowly", "stop the Ferris wheel for 5 sec while the bulbs flash quickly", etc. To solve these problems, students have to use two output ports (bulbs and motor) and one input port (magnetic sensor). The magnetic sensor counts the number of rotations.

3.4.3 The implementation of the study

Our study was realised with 24 students of grade 6 (11 and 12 years old girls and boys) of a primary school in the Netherlands. The students never used Techno-Logica or a comparable product before. The teachers composed diversified pairs. The pre-service teacher acted as a coach during the problem-solving task. He was instructed to interfere as less as possible.

By reading the explanations in the booklet and fulfilling the tasks with the concrete objects and programming software, the students gain enough knowledge of the functioning of the programme (Figure 3.3). After that, they are ready to solve a problem they have never encountered before. Manipulating this hybrid micro world is supposed to activate a thinking process that is converted in concrete programming actions that are verified by testing the concrete model. The virtual and concrete learning space makes thinking behaviour observable. The issues (the traffic lights and the Ferris wheel) are not easy to solve. For that reason, an intense verbal interaction occurs. The interaction is language-based and aimed at solving a problem together. The interaction is goal oriented and based on the development of new knowledge (Slangen & Sloep, 2005). In this "progressive discourse", (Bereiter, 1994) the various participants constantly explore ideas, provide suppositions, investigate alternatives, and search for explanations or solutions that contribute towards progress in the problem solving.

Figure 3.3: Pairs reading the instruction booklet solving the problem of the K'nex Ferris wheel

3.4.4 The observation model

In this exploratory phase of our study, we developed two structured observation tools to proof the presence of the supposed thinking behaviour and to explore the differences in this behaviour shown during the problem solving. A second objective was to test the usability of the observation tool we developed.

We used two checklists to observe the thinking behaviour of the students. The first checklist (Table 3.1) is based on habits of mind as classified by (Costa, 2000). The second checklist (Table 3.2) is based on 18 thinking skills that are partly deduced from the IOWA Integrated Thinking Model (see chapter 2 Figure 2.1 or (Jonassen, 2000)). The coding scheme is built on the interpretation and classification of verbal and non-verbal utterances extracted from the discourse. Therefore, the observer could use a checklist with short descriptions of each category. For example, managing impulsivity is defined as "the pair acts systematically and based on a plan is goal oriented, does not react immediately to sudden utterances or hunches without considering the consequences, strives to clarify and understand what's happening, develops strategies to approach problems, and takes time before acting".

Table 3.1: Habits of Mind

Habits of Mind	
1. persisting	9. thinking and communicating with clarity and precision
2. managing impulsivity	10. gathering data through all senses
3. listening with understanding and empathy	11. creating, imagining, innovating
4. thinking flexibly	12. responding with wonderment and awe
5. thinking about thinking (meta cognition)	13. taking responsible risks
6. striving for accuracy	14. finding humour
7. questioning and posing problems	15. thinking interdependently
8. applying past knowledge to new situations	16. remaining open to continuous learning

Source: (Costa, 2000)

Table 3.2: Thinking skills deduced from IOWA Integrated Thinking Model

Thinking Skills	
Analysing	*Evaluating*
Recognising patterns	Assessing information
Classifying	Determining criteria
Identifying assumptions	Prioritising
Identifying main ideas	Recognising fallacies
Finding sequences	Verifying
Logical reasoning	*Synthesising*
Comparing and contrasting	Analogical thinking
Application of general rules	Summarising
Formulating of general rules	Hypothesising
Causal reasoning	Planning

The problem-solving sessions are videotaped. The recordings of progressive discourse within each pair are analysed. Each minute the verbal and non-verbal interaction is interpreted and the four most striking habits of mind and thinking skills are scored. For seven pairs both problems (level two and three) are scored. For three pairs only the problem on level two, and for two pairs only the problem on level three is scored.

3.5 First results and prospective

By means of Exploratory Data Analysis this case study delivers new starting points to examine the effects of mind tools on learning more deeply. In this section, we mention our first observations, results and conclusions.

- The first question to answer is; is Techno-Logica a useful mind tool to construct teacher independent and PBL?

On the one hand, we observed that there is real PBL. The problems are challenging in a way that students are entirely absorbed. Most students stay motivated also if there seems to be no progress in solving the problem for a while. Students are highly engaged with the task and eager to solve the problem. The instruction booklet was completely teacher independent. On the other hand, during the problem-solving tasks we observed that coaching is regularly given. We assume a part of this coaching to be a result of the proximity of the coach. The task is not easily to solve and sometimes students loosed motivation or reached a deadlock. Some students quickly ask for help and sometimes the coach is not reserved enough. We observed different kinds of coaching, e.g. short hints, open questions, motivating comments, and positive feedback. Occasionally, it is necessary for the teacher to realise a breakthrough moment in stranded thinking. Bearing in mind that learning occurs and supports participating in a social context (social constructivist learning), we prefer an interactive dialogue between students, and between teacher and students. As Slangen and Sloep (2005) emphasised, language is important to put the learners' thoughts into words that make the thinking process explicit so that another learner or teacher can react to that process. Using this task in a regular classroom setting seems possible but needs a flexible teacher who while teaching a whole group of students can coach when necessary a pair working at the task. The role of the teacher and his contribution to the problem solving should be studied in a classroom setting.

- The second question is; can we observe active higher-order thinking and habits of mind in such learning environments?

The answer to this question is surely "yes, we can". Altogether we scored during 19 sessions (10 traffic light sessions and 9 Ferris wheel sessions) 8 scores every minute (4 habits of mind and 4 higher order-thinking skills) which resulted in about 9,000 scores. During the problem-solving task, we noticed an intensive progressive discourse with much active thinking behaviour and continuous reflection. We also noticed many non-verbal expressions of active thinking. By testing their programmes, students are directed repeatedly towards reflective thinking, they discuss solutions, verify, etc. (Norman, 1993) distinguishes between experiential and reflective thinking. Both kinds of thinking are assumed to be present during the problem-solving tasks. Experiential thinking becomes more precise during the self-instruction phase and increases as an effect of the learning process during the problem solving.

- Even more appealing are the answers and discussions to the third question; which types of higher-order thinking can we discern?

The observation tools in this case study are useful to examine thinking skills and habits of mind. We could discriminate between several categories of habits of mind as well as thinking skills.

The first thing, we notice are the considerable differences between the frequencies of the several categories of habits of mind (Figure 3.4). Most used are striving for accuracy (17%), thinking flexibly (13%), persisting (10%), questioning and posing problems (8%), listening with understanding and empathy (8%). Least used are responding with wonderment and awe (2%), taking responsible risks (2%), finding humour (2%), thinking interdependently (3%) and remaining open to continuous learning (2%). We expect these differences to be a result of the kind of mind tool we use and the type of problem-solving task.

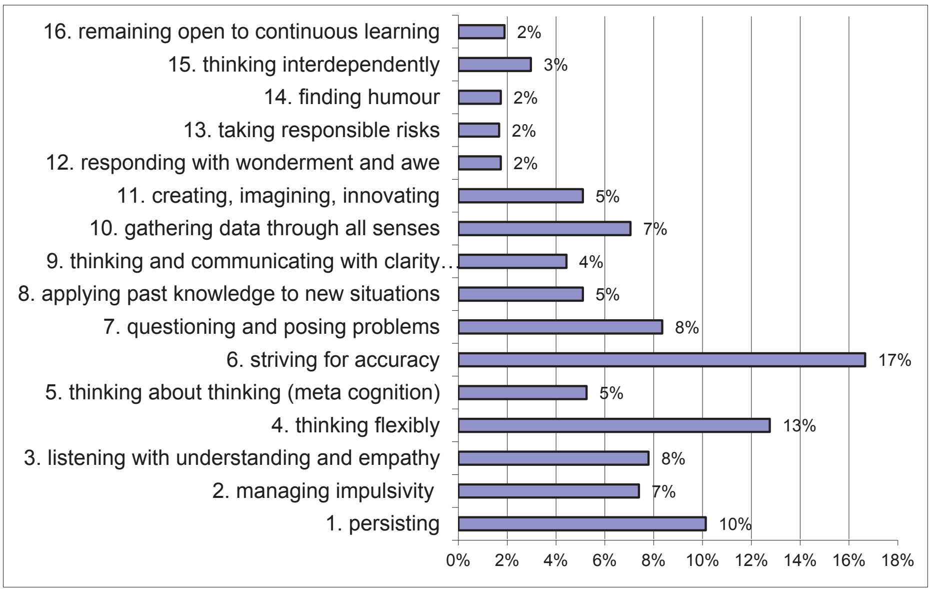

Figure 3.4: Habits of mind relative frequency scores (n = 4610) summarised over all pairs summarised for each category

For example, the hybrid micro world Techno-Logica and the tasks (traffic light and Ferris wheel) give the students opportunities to test their programme as often as wished. Every new test session offers clear visual feedback (the process-monitor of the software and the reactions of the concrete model) on the quality of the last changes in the control programme and on the progress in respect to the problem-solving task as a whole. This testing behaviour could be interpreted as trial and error learning. However, we regard to it as explicit actions to reach a higher level of accuracy. Since, we see students learning from their mistaken reasoning by gathering and interpreting feedback information during the test sessions. There are just a few scores on the category responsible risk-taking. Analysing the tasks, we have to conclude, the students are not confronted with real hazardous situations. On the other hand, what would the result be on the category taking responsible risks if there were a fixed amount of test sessions? Alternatively, if there was a competition component. Would there be more reasoning before testing and would there be a similar qualitative result of the problem-solving task? We expect there would explicit be more reasoning and abstract verifying before the students tested the concrete model. However, would using purely a virtual simulation tool (without concrete feedback) deliver same or just different scores? This example teaches us that we still have many questions to answer in respect to habits of minds, task conditions and used type of mind tool.

Secondly, we also noticed a varying intensity of the scores in some categories concerning the thinking skills (Figure 3.5). Predominantly, high frequencies were found in the main category of higher-order thinking skills “evaluating” (44%). We found lower, nevertheless, robust higher-order thinking skills scores on connecting (22%), synthesising (18%) and analysing (16%). Therefore, we have to conclude the mind tool and task explicitly activates many of students’ evaluating skills. Most used evaluating skills are assessing information (13%), determining criteria (10%), verifying (10%) and recognising fallacies (7%). Least used is prioritising (3%). Our explanation for this is to find in the properties of the task and the type of mind tool we used. Testing the programme and thinking process has much to do with the evaluating thinking skills. As we already mentioned before, the students have unrestricted opportunities to test the programme and model and learn from it during the problem solving session.

Thirdly, at this point in our exploratory study, we assume there is enough active thinking behaviour to conclude that the task and mind tool are appropriate to activate higher-order thinking skills. Nevertheless, in the future it is necessary to do more research on this subject. We noticed a remarkable variety between some scores within the category synthesising. Hypothesising

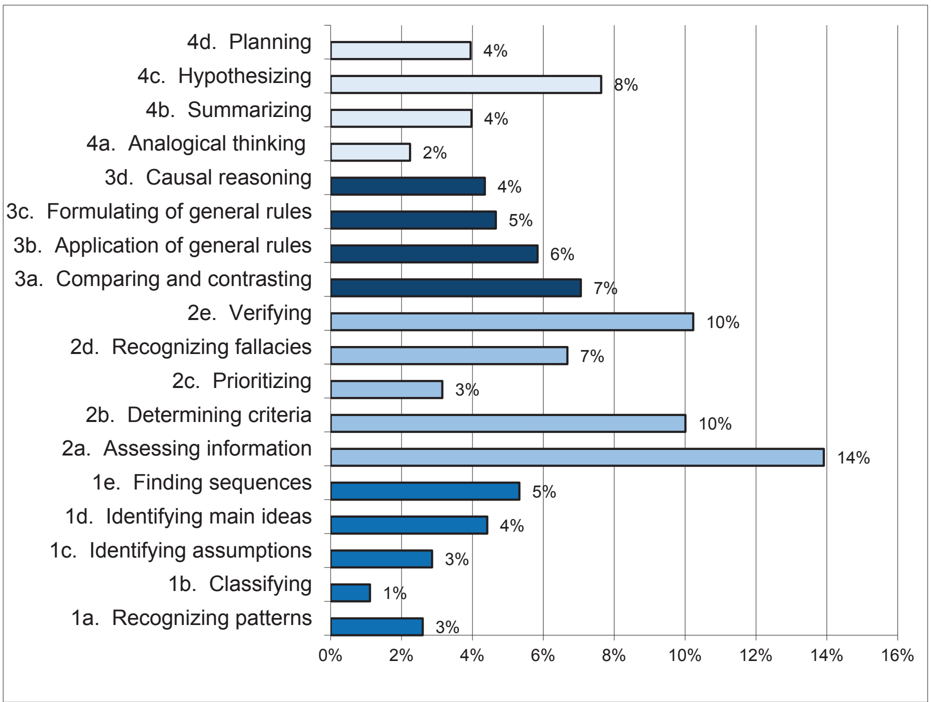

Figure 3.5: Thinking skills relative frequency scores (n = 4566) summarised for each thinking skill category which are further classified in higher-order thinking skills (see colour tints) 1, Analysing 16%; 2, evaluating 44%; 3, connecting 22%; 4, synthesising 18%

(8%) and analogical thinking (2%) are both outmost scores of this. We found an even bigger difference between assessing information (13%) and prioritising (3%) in the category "evaluating". We assume these scores are the result of the task and the type of mind tool. Nevertheless, we still have many unanswered questions. Are scores on Habits of Mind and higher-order thinking skills somehow related? Is it possible to identify several types of mind tools and problem-solving tasks, which stimulate different sets of thinking skills?

Fourthly, the conclusion should be, the task is suitable for developing higher order thinking skills especially evaluating skills. We expect that mastering different sets of thinking skills are the important instruments for expert problem-solvers. If problem- solving and decision-making tasks do not stimulate the mastering of these skills, we should use other tasks and tools. Then the next question is: do we in this case study notice some differences between the two tasks used? The traffic light (mode 2) and Ferris wheel (mode 3) tasks are the same kind of tasks with just more complexity in the defined problem and the programme mode. Especially the interaction aspect of programme mode 3, to process input from the sensor of the Ferris wheel into right actions, is difficult for many students.

We observed a difference in time needed to solve the two problems. The solution of the first problem-solving task (traffic light) was for a few pairs extremely difficult. We noticed a major time range (96 min) between the quickest pair (24 min) and the slowest pair (120 min). The second more complex problem-solving task showed a decrease in the time range (78 min) between the quickest pair (46 min) and the slowest pair (124 min). We suppose that students are learning to solve problems more efficient and quicker. Despite the small number of pairs, this conclusion seems also to be confirmed by a decreasing SD from 29 (traffic light problem) to 24 (Ferris wheel problem).

Observing the scores on thinking skills in case of the two problems, we did see some interesting differences and concordances (Figure 3.6 and Figure 3.7). Comparing the pairs (seven pairs), where scored at both problem-solving tasks, we see a lot of evaluating thinking subsequently 45 and 45% for the traffic light task and the Ferris wheel task. Scores on the category synthesising show a slightly increasing pattern subsequently 16 and 18% between the traffic light task and the Ferris wheel task. However, as we look at connecting we see a substantial increasing pattern subsequently 18 and 23% for the traffic light task and the Ferris wheel task. On the contrary, analysing decreased from 21 to 14%. How is this explainable? Is the first task (traffic light) more confusing and do the students use different strategies and thinking skills? Have the students learned a more effective way of tackling the Ferris wheel problem? Do students have built a knowledge base and show behaviour that is more expert? We think it is plausible that learned knowledge and strategies have led to acquaintance with the computer programme, the type of task, and the relevant content of the concrete technical domain. Hence, there is less requirement and necessity for analysing actions. This also implies that the more complex Ferris wheel task does not demand for more analysing behaviour. The increasing connecting and synthesising behaviour is most likely the result of a more efficient way of using learned knowledge to solve the problem. This is in accordance with the conclusion that despite the complexity of the Ferris wheel task there was average less time needed to solve the problem. Looking separately at the pairs this trend is difficult observable (Figure 3.6 and Figure 3.7). As we see, most pairs show the same or less analysing behaviour. However, the dispersion of the other categories differs per pair.

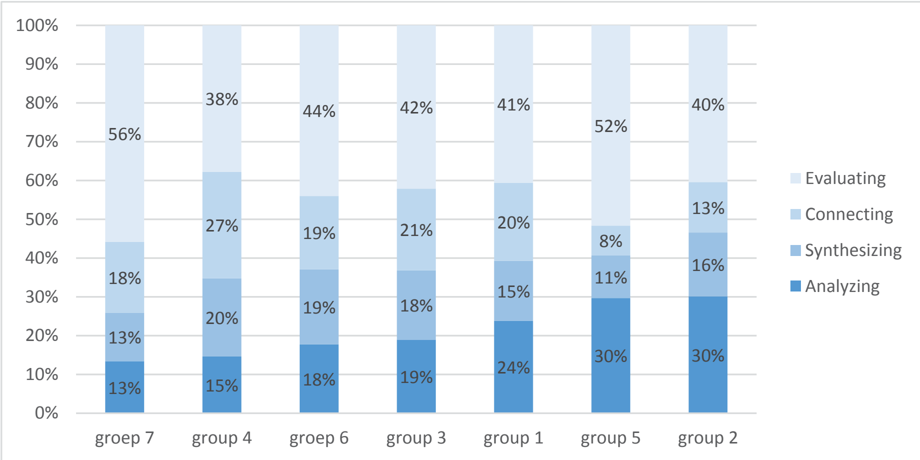

Figure 3.6: Dispersion of higher-order thinking skills (relative frequency) scores per pair for traffic light problem-solving task in a cumulative column graph

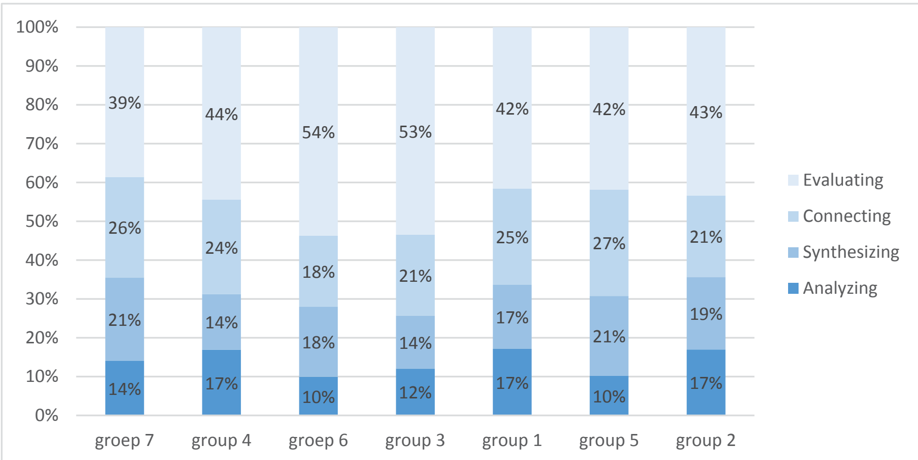

Figure 3.7: Dispersion of higher-order thinking skills (relative frequency) scores per pair for Ferris wheel problem-solving task in a cumulative column graph

The results of the case study taught us there are explicit frequency differences in the used habits of mind and thinking skills. At this point, we do not know how these differences relate to the quality of the problem-solving task. At least we expect they do. The next question could be: is there a difference between mind tools such as pure virtual simulations vs. the hybrid micro worlds? Our future aim is to study these phenomena in more depth using different tasks and types of mind tools.

3.6 Conclusions

We conclude by summarising the results. Our experience during the case study shows that the observation instruments are usable to score aspects of the thinking behaviour. Altogether, we found a substantial volume of active thinking behaviour. At this moment, we conclude that the problem-solving task of the kind we used forces the students to activate some of the habits of mind more than others. The same is to say about thinking skills. A research question that we like to pose as outcome of this case study is the following. Do different types of micro worlds and even different kinds of mind tools activate different aspects of thinking? If the answer to this question would be “yes”, schools should confront students with different kinds of mind tools. The purpose of this all is to activate different components of thinking behaviour and stimulate learning. These mind tools can vary within a class of tools such as dynamic modelling tools (micro worlds), semantic organisation tools, conversation tools and information interpretation tools. They can even vary within one class like dynamic modelling tools. Hybrid micro worlds, virtual micro worlds, simulation software, etc. could be used.

With the gathered information it is not possible to conclude anything about what (Niaz, 1995) described as the “content-process dichotomy”. The question if learning and thinking can exist without content is essential. Woodhouse (1991) formulates that it is a fallacy to suppose that generic thinking skills can exist without context. The time differences between the two problem-solving tasks points slightly at an increasing domain specific knowledge during the tasks (more complexity less time needed). Therefore, we think it is plausible to state that the variety in using different categories of thinking behaviour (processes) is influenced by the type of content.

For this reason, it is important to carry out much more research on problem-solving tasks with dynamic modelling tools such as micro worlds or simulation software. There are several indications that these tasks stimulate more and different thinking behaviour than regular scholastic tasks. We support the presumption that thinking is learnable and a teacher can stimulate and educate it by using adequate tools and strategies. However, we should not study these skills with the intention to train them separately. The holistic view on learning teaches that human thinking is more than the sum of component skills. It is regrettable that teachers are not used to teaching with mind tools. We expect that it is possible to change this situation by means of involving pre-service teachers.

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Chapter 4: What students can learn from working with robotic direct manipulation environments*

Abstract

This study investigates what students aged 11–12 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 students' 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 students' reasoning patterns. There is ample evidence that students have little difficulty in understanding that robots are man-made technological and functional artefacts. Students' 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 students' developing technological literacy and the possibilities for teaching and learning in primary education.

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4.1 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 & Young, 2002; Rocard, 2007). Several definitions of technological literacy circulate but all emphasise knowledge, ways of thinking and acting, and capabilities (Dugger & Gilberti, 2007; Garmire & Pearson, 2006; Jones & 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 students' technological literacy. Robotics is widely considered to be one of the "big ideas" of present-day science and technology (Dijkgraaf, Fresco, Gualthérie van Weezel, & van Calmthout, 2008; Hacker, de Vries, & Rossouw, 2009). Moreover, students will encounter robotics all their lives. Hence, robotics is relevant to primary education. To answer the question of what students (aged 11–12) 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 students' developing conceptual understanding and established a dialogical teaching context in which students explored robots and programs and solved robot design problems with Lego Mindstorms NXT, which functions as a dynamic modelling tool and as a Direct Manipulation Environment (DME) (Jonassen, 2006; Slangen, van Keulen, & Jochems, 2009). From previous research we know that such an environment elicits intense discourse and thinking (Slangen, Fanchamps, & Kommers, 2008). Our study is explorative in nature and yields insights into how students' conceptual development can be stimulated and enhanced by suitable tasks, discussions and teacher interventions.

4.2 Theoretical framework

4.2.1 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 students (Gifford, 2005; Vanderborght, 2008). Many science and technology educators advocate that such big ideas should receive more attention in the school curriculum (Kipperman, 2009). Students themselves are well aware of the necessity of learning about robotics because of their likely ubiquitous presence in future society (Shin & Kim, 2007). Economic, technological and social perspectives urge schools to prepare students for robotics (Verlaan et al., 2007). Automated systems should be an item in the primary school curriculum (Boeijen, Kneepkens, & Thijssen, 2010). This justifies precious time in school being devoted to robotics.

4.2.2 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 & Young, 2002). In order to attain this functional understanding of technology, it is important to use the design cycle in engineering (van Graft & Kemmers, 2007). Walma van der Molen, de Lange, and Kok (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 analyse problems, develop solutions and learn from experiences. Furthermore, learning is greatly enhanced when students 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 students' understanding of robotics (Ackermann, 1991, 2000; Levy & Mioduser, 2008; Mioduser, Levy, & Tallis, 2009; Mioduser, Venezky, & Gong, 1996; Resnick & Martin, 1991), stressing the importance of interaction with concrete materials.

We therefore suppose that robotics may best be learned by having students work in a context with realistic robotic problems including designing, constructing, programming, testing and optimising, and not just by talking or reading. Moreover, we suppose that teachers have to scaffold students' learning by asking questions, providing feedback, pointing out inconsistencies, and elaborating on experiences and information, that is, dialogical teaching which stimulates and extends students’ 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.

4.2.3 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 analysing, synthesising, evaluating, and causal reasoning (Savage, Sánchez, O'Donnell, & Tagney, 2003; Slangen et al., 2009; Slangen et al., 2008; Sullivan, 2008). Robotic DMEs provide a potentially rich context for learning scientific or technological knowledge (Hamner, Lauwers, Bernstein, Nourbakhsh, & DiSalvo, 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 & Price, 2004), for understanding concepts of robotics (Ackermann, 1991, 2000; Levy & Mioduser, 2008; Mioduser et al., 2009; Mioduser et al., 1996; Resnick & Martin, 1991), and for developing general problem solving skills in the context of science and technology (Barak & Zadok, 2009). Lego Mindstorms NXT robotics (Astolfo, Ferrari, & Ferrari, 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 children are able to work with such tools and arrive at an understanding of robots’ emergent behaviour (Mioduser et al., 2009).

4.2.4 A conceptual framework for robotics

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

Many students' 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, p. 3).

For Levy and Mioduser (2008), who focus on young children of kindergarten age, this differentiation between two logically opposed conceptualisations suffices. In our study, we focus on older students, 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, Dannenburg, van Boxtel, & Horn, 2008; van Lith, 2006; Vanderborght, 2008). A robot is characterised 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 & Zadok, 2009; Hacker & 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 & 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 student's ideas of robots: the psychological, technological, function, and controlled system perspective. Addressing this is pedagogically important in developing a more advanced and versatile conceptualisation of robotics.

Psychological perspective: robots are animated creatures. Students 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 recognises 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.

4.2.5 Learning objectives

Being functionally technologically literate with respect to robotics implies that students 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, students should gradually understand that:

1. Robots are artefacts, that is, they may appear to be animated but robotic behaviour is based on technology (the technological perspective).
2. Robots are functional, that is, they are characterised 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).

4.3 Research questions and methodology

In this study, we explore two questions. (1) What do students 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 students’ 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 students 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 students 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 students' learning processes and conceptual learning outcomes in detail. We aimed to collect data on student's activities, discourse, reflections and achievements in this educational context. Derived from theory on one-to-one teaching experiments (Cobb & Steffe, 1983), we designed a one-to-two teaching experiment: one teacher/researcher and two students. This allowed us to probe students' developing understanding better by analysing their mutual interactions and those with the teacher: "in the course of an interaction, both the teacher and the students attempt to make sense of each other's verbal and nonverbal activity" (Cobb & Steffe, 1983, p. 85).

From literature and previous experiences with elementary school students, we had explicit and tacit expectations about what students 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 students conceptualise robots? We hypothesise that students know that robots are technological man-made artefacts and that they use both psychological and technical language to describe robots.
2. Are students able to develop a functional point of view? We hypothesise that students 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 students perceive robots as integrated systems? We hypothesise that it would be difficult for students to consider systemic effects such as interactions between various parts.

4. Do students understand that robots are controlled by a program? We hypothesise that students know that robots contain a program written by humans. However, they may not know what a program really is.
5. Are students able to understand and apply the Sense-Reason-Act loop? We hypothesise that understanding the nature of the sensory input necessary for logical reasoning processes to decide upon actions, would be rather difficult for students.

The actual teaching experiment consisted of six 2-h lessons (Table 4.1) which were conducted during normal school hours but outside the classroom with pairs of students, age 11–12, in the last year of elementary education (grade 6) 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 students' 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 fulfil a certain task.

In lesson one we explored the students' existing knowledge by talking about and examining various examples of robots. Furthermore, we drew students' awareness to the function and system aspects through the students comparing two outwardly identical robots which behaved differently. In the second and the third lesson the students 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 behaviour of ready-made programs of different complexity. In the fourth lesson we presented students 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 students' ability to analyse 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 optimising the program.

Table 4.1: The lesson plan and research goals

Lesson	Goals	Activities
1	Part 1: Probe students' initial perspectives on robotics. Part 2: Probe students' initial understanding of the controlled system perspective	Interactive discourse between teacher and two students about robotics. Analysis by the students 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 students 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.	Students analyse 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 students 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, build the robot.
5	Probe whether students' understanding of the functional perspective, the controlled system perspective and the S-R-A-loop is elaborated when students build and test robots.	Testing the robot, focusing on deficiencies and optimising the robot with respect to functional analysis, design, construction and program.
6	Similar to lesson 5	Similar to lesson 5

The first author, who acted as a teacher, conducted the lessons. Through confronting the students with robots, through open questions and focused remarks, the students' attention was drawn to certain features and, in general, students were encouraged to speak and act. The teacher tried to stay within the zone of proximal development of the students (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 students, their mutual interactions, the construction and testing activities and the conversations with the researcher. A webcam recorded the student'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 (Glaser & Strauss, 1967). This methodology is suitable for analysing and explaining discourse and actions of participants. Verbalisations 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 students' conceptual understanding of robots in more detail with the hypotheses. We explored students' 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 students' understanding were transcribed in full and discussed in the research team. Emerging interpretations on students' 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.

4.4 Results

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

4.4.1 Perspectives students use

In the first lesson our intention was to unravel which perspectives students use or do not use. The researcher started an open dialogue to explore students' conceptualisation 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 students 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 4.2.

Table 4.2 Prevalence of perspectives in the first lesson

	Psychological perspective		Technological perspective		Function perspective		Controlled system perspective		
	n	***%***	***n***	***%***	***n***	***%***	***n***	***%***	***Total***
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

Not unexpectedly, the students predominantly used descriptions and words referring to the psychological, technological, and function perspective, but the more advanced control system perspective also emerged. Students 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 students showed an understanding of robots as controlled interactive technical systems. We probed the psychological perspective, since students regularly use words and phrases consistent with this perspective: robots "can see", can "be afraid", "can walk" et cetera:

Student 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.

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

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

Students said "the robot looks" instead of "the sensor detects", "the robot thinks" instead of "the program compares". However, when students 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? Student 6: He sees us with the sensor. Student 5: He sees us with his eyes. Student 6: No, these are feeling sensors.

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

> *Student 2: This is the sound sensor. Researcher: What is a sound sensor? Student 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 students. We conclude that these students know that robots are programmed artificial constructions, although they regularly use humanoid characterisations and descriptions. In this, they do not differ much from mature engineers.

4.4.2 The function perspective

It proved to be rather difficult to focus students' attention on functionality in the sense of conducting a specific task or solving a specific problem through appropriate behaviour of the robot. Students 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? Student 7: They make robots for competitions. Researcher: Do you know more? Student 8: Toys for students.*

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

> *Researcher: What makes a robot a good robot? Student 6: It must be able to talk…. Student 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 students. "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? Student 1: To work in factories, pick things up from the conveyor belt and put it on another one.*

Only a few students 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? Student 1: Yes that it can do something, that it is useful for something. Student 2: That is does what is assigned.*

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

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

In this conceptualisation, 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 students 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 students' concept of functionality as a key concept in understanding robotic systems. The next lessons had students solving problems. These indeed led to clearer conceptions of the function perspective. While designing, constructing, programming and testing the robot, the students 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? Student 5: Yes, he must locate the island on the black floor. Student 5: Yes. Researcher: Here is an island [white sheet of paper] and a black floor. Student 5: And when he locates the island a flag has to fly on top.*

> *Researcher: And how would the robot find the white island? Students 1 and 2: With the light sensor. Researcher: And how did you discover that there is a light sensor? Student 2: We thought about a light sensor, which would be able to search the floor for bright colours, because the floor here is brown. Student 1: And white is bright. Student 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 students' 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.

4.4.3 The system perspective

In the next step, we probed students' (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. Students 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 students a robot initially was what it does:

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

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

Seeing, feeling, and driving are characteristics of the whole robot but are brought about by different subsystems. By having students compare robots that appear similar but behave differently, and giving the students the task to make the robots act identically, we drew students' 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 students of this age possess the necessary analysing, 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, students 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? Student 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. Student 1: [connects the wire again] When we let him drive again it should work again. [performs this test] Student 1: Yes, it works again.*

In the last three lessons, we operated the other way round and asked students to develop a robot from scratch that was able to perform a pre-defined task in a given context, "The island task" (Figure 4.1).

To solve this problem, students analysed 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, students 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 recognise that parts and systems, especially constructive elements, the control system, and the S-R-A loop have to be adapted to each other:

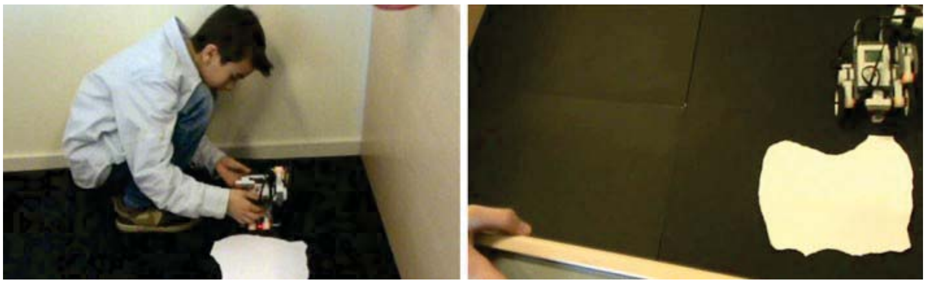

Figure 4.1: The island task

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

[Students 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? Student 5: Here, port A, B or C. Researcher: What is it? Student 6: Yes, one motor is connected to port A. Student 5: Because the real motors [points at the wheels] are connected to B and C.

> *[Analysing a bug in the program] Student 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 students to reflect on the coherence between separated systems, subsystems and parts. However, these signs of system thinking appeared infrequently and not with all students. It was not yet a conscious approach to robotic problems for all students.

4.4.4 The controlled system perspective

People tend to use categories like emotion, feeling and intelligence to describe the behaviour of simple, autonomously operating vehicles (Braitenberg, 1984). In line with this, we expect that students will not articulate their knowledge of programs spontaneously but use terms like "think", "know", "feel", or "want" instead. This may hinder students 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 students' 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 (Figure 4.2), 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 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 students 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.

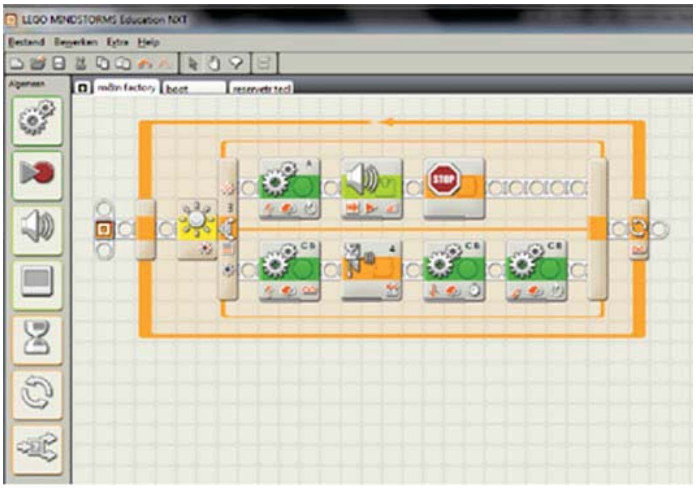

Figure 4.2: An example of a Lego Mindstorms NXT program to find the island and raise the flag

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

Student 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 students 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]? Student 1: It can be that you put something different in this one. Student 2: Yes, differently programmed.

Researcher: What are programs? Student 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 students 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 students to analyse and predict the robot's behaviour and subsequently test that prediction. As expected, most students 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] Student 3: Rotation time is 0.5, maybe we can …. I am going to try if it succeeds with 4. Student 4: I try 0.6? Student 3: Wait a moment. Researcher: 4? Student 3: 0.4. Student 4: He is now riding lopsided. He is still increasingly lopsided. It must be bigger than 0.6.

When students recognised 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 students did not require much explanation to recognise the relation between preferred output and programmed instructions. They developed an insight that actions depend on parameters and values specified in the program.

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

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

In their first lessons, students predominantly created R-A programs using "move" blocks only. With some help students 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? Student 7: Two. Student 8: You must use the iteration and then set it at two. Student 7: Or do we set it at 200, then he turns a hundred squares?*

Initially, for students, 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 students 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 students. 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? Student 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. Student 4: Then we must increase it [parameter time]. Researcher: Look for other solutions. Student 3: No, we have to change this [parameter time] to "unlimited". Researcher: What is "unlimited"? Student 3: That it goes on running and then the ultrasonic says "stop now". Otherwise you run against the wall. Student 4: Oh yes.*

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

> *Researcher: Does the robot stop with the sensor? Student 3: I removed the sensor.*
>
> *[The students try to use a sensor block but without the desired effect] Student 8: Maybe we have to know how many seconds it takes. Student 7: I think it is not more than 60 s. Student 8: Otherwise you have to count. Student 7: But it also depends on the distance from the starting position.*
>
> *Student 4: We must change the starting position. [Student 3: moves the robot closer to the island].*

We conclude that students 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 students 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 students for a subsequent step: solving problems with conditional reasoning.

4.4.5 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 fulfilment, 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 students 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 students 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 students understood that sensory input and a program are responsible for halting:

> *Researcher: What does this robot do? Student 4: In some way he can see. Student 3: He stops when this is in between. Researcher: Between what? Student 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 students' attention was focused on how sensors may cause halting or changing actions, they were able to grasp the meaning of items in existing programs:

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

Researcher: If that ultrasonic sensor detects a wall at 20 cm, what happens? Student 4: It stops, it should stop. Researcher: It should stop but does it stop? Student 4: No. Student 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 students attempted to program static and sequential actions. We observed that several students were able to adopt this new approach.

Student 3: He runs first. Student 4: He follows the blocks. Researcher: What does he do in the blocks? Student 4: He follows them. Student 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. Student 4: Backwards. Student 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 students 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 students 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 students 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 students 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? Student 4: That is it, I think. Student 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. Students 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." Students grope for this language with conjectures like: "If the sensor sees the white colour, 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.

4.4.6 Summary of results

We conjectured that students know that robots are man-made artefacts 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 students' 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, students 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 students 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 students 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. Students 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 students to perceive robots as integrated systems and to anticipate interactions between various parts of the robot. Most students in our study do not spontaneously and consciously use systems thinking to approach design, construction or programming problems and tasks. However, students 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 students recognise 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 students know that robots are somehow programmed by humans but will have no clear understanding of what a program really is. Students 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. Students 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 on their own. Many students 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 students. Programming an S-R-A loop is based on the ability to analyse 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 students. When the analysis of the real world problem is phrased in more technical language students seem to understand the S-R-A conditional reasoning structure. However, it depends upon the complexity of the problem whether students are able to convert this into a program.

4.5 Conclusions and discussion

In this study, we argued that it is important for students, 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 students' understanding of robotics and designed a lesson plan that would allow students 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 students to manipulate, reason, predict, hypothesise, analyse and test. Students 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 students 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 students aged 11–12 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. Students' interaction with a peer and a teacher stimulated reflection and helped to build grounded and shared concepts.

In our study, the students 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 students can open a black box, an artefact 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 students for modern-day technological society (Garmire & Pearson, 2006). The practical activities to compare robots, to reconstruct a robot, to analyse a problem, to design, build, and program a robot helped students to become more competent users or practitioners of this technology. In this sense students developed a functional technological literacy. These students, we presume, will recognise robotics in everyday life and understand important concepts such as “design”, “function”, “system”, “structure”, “optimisation”, and “specifications” more easily (Hacker et al., 2009).

In our study we interacted with students 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 students’ conceptual development. In retrospective analysis, we presume we know better which phenomena attract students’ attention and how we can organise dialogues to help students 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 students 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 students aged 11–12. Hence, wide generalisation 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 students 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 students, 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 students will have to pass through conceptions that are not-yet-function, not-yet-system, not-yet-control, 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.

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Chapter 5: Preparing teachers to teach robotics in primary schools*

Abstract

Teachers have an important role in preparing students for a future in which they will encounter robotics everywhere. This study reports on an investigation whether it was possible to prepare in-service teachers for a pedagogy on robotics. Therefore, a training course for primary teacher was developed and conducted. We examined if and how these teachers could acquire subject matter knowledge (SMK), pedagogical knowledge (PK), and pedagogical content knowledge (PCK). We drew several conclusions which pointed at a positive evolvement with respect to becoming more knowledgeable with respect to SMK, PK, and PCK. Teachers also reported positive with respect to their self-efficacy, and their technological and scientific literacy.

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5.1 Introduction

Science and technology play an important part in present-day society. People need some degree of scientific and technological literacy to cope with the challenges and possibilities of the many products, devices and processes available. Robotics is a good example of this. For many people it is a black box. The way it functions is hidden under its superficial appearance, which may be that of a coffee machine, a squeaking baby doll, or a thermostat. People may learn to push the right buttons but remain unaware of what goes on underneath. Such ignorance may alienate people from technology. Primary schools can play a decisive role in preparing children for their future, yet science and technology do not have a strong focus in primary education. Examination of learning and teaching robotics illuminates the problems encountered in improving technological literacy through primary education.

We are in the process of preparing a teaching experiment on robotics in primary schools. In relation to this, we investigate in this paper whether it is possible to prepare teachers adequately to implement the intended pedagogy with the help of an in-service teacher education course that we developed. In view of the forthcoming teaching experiment, we were especially interested in the content and character of the knowledge, insights and attitudes of the teachers. We therefore capitalised on qualitative measures. We report how teachers developed the required knowledge and skills in three domains, i.e. subject matter knowledge, pedagogical knowledge, and pedagogical content knowledge. We examined whether teachers were able to accommodate the content knowledge, concepts and approaches we proposed, whether they developed a personalised version of pedagogical content knowledge, and whether they increased their pedagogic ability with respect to scaffolding students' learning of robotics. We draw some conclusions with regard to the professional development of primary school teachers in areas of science and technology with which they in general are unfamiliar.

5.2 Theoretical Framework

5.2.1 Learning and teaching robotics

Several studies show that children in primary education can learn to open black boxes and develop technological literacy with respect to robotics and automated systems (Krumholtz, 1998; Levy & Mioduser, 2008; Mioduser, Venezky, &

Gong, 1996; Nourbakhsh, Hamner, Lauwers, Berstein, & Disalvo, 2006; Petre & Price, 2004; Resnick & Martin, 1991).

Robotic direct manipulation environments (DMEs) can activate students' higher-order thinking (Slangen, Fanchamps, & Kommers, 2008) and conceptual development (Slangen, van Keulen, & Gravemeijer, 2010). A robotic DME such as Lego Mindstorms NXT (Astolfo, Ferrari, & Ferrari, 2007) is a toolkit with which students can build and program robots. Its effect largely derives from the stimulus to facilitate reciprocal interaction between students and between student(s) and teacher when discussing the manipulative materials. Therefore, students may learn robotics best when working on realistic robotic problems including designing, constructing, programming, testing and optimising, and at the same time having a discourse in cooperative learner-learner or learner(s)-teacher situations. Teachers best support such a learning process by means of scaffolding and dialogic teaching (Alexander, 2008; Lepper, Drake, & O'Donnell-Johnson, 1997; Wyeth, Venz, & Wyeth, 2004; Xun & Land, 2004). For that reason, teachers themselves need knowledge of what students have to learn about robotics and how students learn this.

Consequently, one may distinguish between subject matter knowledge (SMK), pedagogical knowledge (PK), and pedagogical content knowledge (PCK) (Carlsen, 1999; Park & Oliver, 2008; Rohaan, 2009; Zeidler, 2002). Teachers' SMK is shaped through the quality and quantity of information, conceptualisations, and constructs of the particular domain (Zeidler, 2002). Teachers' PK is the understanding of generic instructional variables such as classroom management, pacing, questioning strategies, et cetera (Zeidler, 2002). PCK is defined by Shulman (1987) as an amalgam of SMK and PK. The core of PCK is the teachers' understanding of the way students best learn the concepts of a certain domain and how they overcome learning difficulties (Rohaan, 2009).

5.2.2 Teaching conceptual knowledge in a constructionist context of robotics

Social constructivism postulates that knowledge development is the (re)construction of personal mental models and concepts under the influence of experience and discourse (Bodner, 1986). Concepts and conceptual change derive from the use of analogies, imagistic representations, thought and material experiments and (mathematical) analysis and reasoning (Nersessian, 2008). Students develop shared conceptions to make sense of the surrounding world and to communicate successfully. Experience and active manipulation of tangible objects are presumed to be helpful (Papert, 1993), as are teachers' questioning and inquiry strategies (Xun & Land, 2004). “Children don’t get ideas; they make ideas” (Kafai & Resnick, 1996, p. 1). The robotic DME encourages students to construct and reconstruct concepts through manipulating the robotic material environment. Students appeal to their conceptual knowledge to find solutions, in the meantime changing or refining these concepts as a result of experience and reflection (Norman, 1993). Therefore, concepts are tools to tackle problems as well as learning outcomes of that same process.

Conceptual learning is reinforced when an empathic and well-informed teacher engages in dialogue with the learners, focuses students’ attention on important phenomena and concepts, and helps to make tacit understanding explicit. Teaching for conceptual development is a much more difficult and subtle process than delivering information through direct instruction. Learning to teach for conceptual development can also be seen as a constructivist endeavour that can be supported by engaging teachers in meaningful experiences and reflective discourse.

5.2.3 Subject matter knowledge in robotics

Proficient teachers know why and which conceptual subject matter knowledge is of importance to students learning robotics. In a previous study, we showed that solving problems with robotic DMEs involves students’ understanding of the core concepts “Robot”, “Function”, “System”, “Control” and “Sense-Reason-Act Loop” (Slangen et al., 2010).

Robot. A robot is a material construction of sensors, processors, actuators and algorithms that performs predefined tasks in interaction with an ever changing outer environment (Wisse, 2008). Robots are sophisticated technical systems that function autonomously or by remote control. Teachers need to recognise that students often tend to approach robots as animated entities with human or animal characteristics such as volition, consciousness, intention, emotion or reflexes, and consequently this may hinder their comprehension of robotics (Ackermann, 1991, 2000). Teachers can help students to develop from a more psychological conceptualisation towards a more technological conceptualisation.

Function. From a technological perspective, function is “the action or purpose for which something has been designed, or that users ascribe to it” (Hacker, de Vries, & Rossouw, 2009, p. 55). Students use “function” with different connotations and teachers need to be aware of this. Function in robotics can refer to (1) underlying processes that make up the internal activity of a robot, (2) external activities or roles of the robot, (3) the major objective as the sum of all internal and external functions, (4) the contribution to a larger system, (5) a feature to adapt or reproduce itself (Mahner & Bunge, 2001). Having a well-developed function concept helps teachers to support students to analyse the actions a device (robot) or sub-device has to fulfil in order to serve its purpose.

System. Anderson and Johnson (1997) describe a system as a group of interacting, interrelated, or interdependent components that form a complex and unified whole. A robot is a system constituted of tangible, interrelated and interdependent components as well as intangible processes, interactions, relations and information flows. Robotic DME problems can confront students with phenomena that help them to develop insight in the goals or functions, the order within and between, the fundamental structures, the information flow and relations between (sub) systems, and the system feedback processes. In this way, students understand that systems have input, processes and output, and that a system is a dynamic structure in which actions are the results of its design. Teachers can help students to explore and analyse phenomena that relate to system effects and discover and recognise patterns.

Control. The concept of control is fundamental in understanding the specific nature of automated or robotic systems (Mioduser et al., 1996). Firstly, control refers to a process: the power a person or a device has to influence the actions of a system, its components or related systems. Secondly, it refers to the device that is designed to regulate a system, e.g. a programmable logical controller (PLC). Control mechanisms regulate the state of a system by comparing the value of pre-set variables with the actual input values and executing predefined algorithms that generate output. Understanding the concept of control means being able to translate an intended functionality into a programmable rule or algorithm. Even if the icon-based programming language of Lego Mindstorms in terms of its “grammar” and “syntax” is quite simple, teachers may challenge and support students' in-depth reasoning.

Sense-Reason-Act loop. The Sense-Reason-Act loop is the most defining robotic concept. A robot is a system based on 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). This mechanism represents the interaction an artefact like a robot has with a changing or (partly) unknown environment. The human method of influencing the environment by means of perceiving, reasoning and acting is by proxy conducted by a technological device, the robot. The S-R-A loop implies that sensing continuously generates new information that is fed into the “reasoning” facility, which in turn enables consequential actions. There are, however, fundamental differences between the S-R-A process of a robot (which always follows an algorithm) and humans who use consciousness and will to interfere with the environment. Teachers can help students to understand this difference by reflecting on their experiences with the robotic DME.

5.2.4 Pedagogical knowledge and scaffolding

In a previous study, we showed that students can design, build and programme robots that solve a problem in reality, and that discourse with other students and a proficient teacher leads to conceptual development with regard to the concepts described above (Slangen et al., 2010). To achieve such outcomes in a design- and inquiry-based setting, teachers need pedagogical knowledge and scaffolding skills (Lepper et al., 1997; Wyeth et al., 2004; Xun & Land, 2004). Learning objectives that focus on students' conceptual knowledge development through inquiry and design require teachers who stimulate and (verbally) scaffold exploration and explication (Barnes & Todd, 1995; Vosniadou, Ioannides, Dimitrakopoulou, & Papademetriou, 2001; Wells, 2002). Scaffolding techniques build on (1) intelligent and informed tutoring, (2) nurturing an affective relation, (3) Socratic dialogues (4) raising students' attention and awareness of relevant phenomena, (5) open, non-instructive communication, (6) reflection on results and processes, and (7) encouraging and motivating students (Lepper et al., 1997).

5.2.5 Pedagogical content knowledge

We define pedagogical content knowledge (PCK) as personal knowledge of teachers formed by the fusion of subject matter knowledge, pedagogical knowledge and knowledge of the context. An example of PCK from the domain of robotics is as follows. Novices often solve robotic problems by programming long linear structures ("do this, then do that, then …") (Slangen et al., 2010; Wyeth et al., 2004). Even when students know about the availability of iterative or conditional program codes (often using "if this, then that" types of reasoning) they do not use them, even though they may shorten or improve the program. Apparently, students still lack such structuring capacities. Teachers should be aware that students tend to solve problems by programming action after action. Experts solve such problems by searching for repetitive and conditional structures and by developing these into subsystems that each has its own individual input and output. Teachers can help students to overcome their difficulties with iteration by asking questions such as "Does the robot have to do things that happen more than once?", "What must the robot do if it hits the wall?". Teachers who know this type of learning problem can recognise it in practice and stimulate conceptual development, if they possess relevant PCK. For this study, PCK is required that enables teachers to help their students elaborate their imprecise or anthropomorphic previous knowledge into conceptions that rely on function, system, control and sense-reason-act looping, in a context that is defined by an inquiry- and design-based pedagogical approach.

5.2.6 Professional development in relation to robotics

In this study, we presume that developing scientific and technological literacy with regard to robotics requires teachers who have the appropriate subject matter knowledge, pedagogical knowledge and pedagogical content knowledge outlined above. Such teachers and corresponding teaching practices are not, however, available in abundance. On the contrary, although robotics may be important for society, it is not widely taught in primary schools in the Netherlands and most teachers have little or no experience of teaching robotics. Currently, it is difficult if not impossible to investigate how teachers develop students' understanding of robotics in day-to-day classroom settings.

Teachers normally generate pedagogical content knowledge from their own teaching practice but it can also be acquired through professional development (Smith, 1999). Intensive and comprehensive professional development programs can be effective in transforming teachers' ideas about teaching and learning as well as their teaching practice. In particular, teachers can be assisted to shift from a teacher-centred approach relying on instruction to a more learner-centred approach, such as inquiry- and design-based learning, and to align all the elements of the teaching situation in order to achieve positive learner outcomes (Hackling, 2007; Prebble et al., 2004; Stes, Clement, & Van Petegem, 2007). Kirkpatrick (1996) suggests dividing the impact of professional development into how teachers react, what they learn, what they do, and what the results are.

5.3 Research questions and methodology

In this chapter we report on a qualitative study that explores how experienced teachers learn to teach robotics. The main research question is: "How do primary school teachers develop the ability to support students' inquiry- and design-based learning of robotics?".

We assume that a proficient teacher requires subject matter knowledge, pedagogical knowledge and pedagogical content knowledge to be outlined in the theoretical framework. Learning to teach robotics implies improving these capacities, and a professional development approach may be instrumental in achieving this aim. Regarding the intended teaching experiment we decided to develop and execute a course for in-service teachers that should help us answer the following research questions:

1. How do teachers acquire the subject matter knowledge (SMK) they need?
2. How do teachers elaborate their existing pedagogical knowledge (PK) into an approach that suits the requirements of inquiry- and design-based teaching, i.e. a scaffolding approach?
3. How do teachers develop pedagogical content knowledge (PCK) with respect to function, system, control and sense-reason-act?
4. How does the professional development trajectory influence teachers' attitudes and self-efficacy with regard to teaching robotics in class?

From a research point of view, data gathered during this course should contribute to educational theory on how teachers in primary education can develop pedagogical content knowledge in the domain of science and technology. To meet this objective, we capitalised on qualitative parameters that informed us about the three processes that are especially relevant. Firstly, we had to provide teachers with information on robotic concepts and on students' conceptual development in solving robotic problems in an inquiry- and design-based setting. Secondly, we had to activate and elaborate teachers' scaffolding knowledge and skills, and thirdly we had to confront teachers with robotic problems in order to help them recognise and tackle the conceptual problems that students may have in such situations, and help them construct relevant personal pedagogical content knowledge.

Kirkpatrick (1996) developed a four-level model for the impact of professional development and our course focused on the first two levels, that is, (1) on how teachers reacted to the course and its content and (2) on what they learned from it. In a subsequent study, we will focus on the two next levels, (3) behaviour in the classroom and (4) student learning outcomes.

Instruction can be an effective strategy to provide teachers with the information they require, but it may fail when teachers have to construct new concepts. Just like students, teachers learn more effectively when they are able to explore their own questions, design solutions to problems, and are stimulated to explicate their ideas.

Furthermore if the processes mentioned above were well chosen and well executed, then the behaviour, discourse and opinions of the participants would help to answer our research questions. Each process had its own presuppositions on effectiveness and a consequent approach, outlined below.

5.3.1 Acquisition of knowledge

In order to be able to teach robotics in a design- and inquiry-based setting in primary schools, teachers should have subject matter knowledge of robotics and knowledge of students' conceptual development. In the course, we provided much of this information through reading assignments, short presentations and video fragments showing students solving robotic problems in interaction with each other and an experienced teacher (the first author). Our conjecture was that primary school teachers are able to understand the information provided, and that they are able to enlarge their knowledge of the concepts during subsequent problem-solving activities.

5.3.2 Activating scaffolding skills

Experienced teachers have a large repertoire of teaching skills. We assumed that the participants would be familiar with scaffolding in general, although they might have relied on direct instruction methods in the context of teaching science and technology and never tutored students' learning processes in robotics. We conjectured that they would adapt and elaborate their pre-existing generic skills to robotics when we showed examples of successful scaffolding on video and practised scaffolding techniques ourselves during the assignments with the teachers.

5.3.3 Development of pedagogical content knowledge

The participants were informed about the conceptual difficulties students experience when solving robotic problems. We conjectured, however, that this would not be sufficient to enable them to recognise and adequately react to the conceptual problems that might occur in the teachers' own teaching practice. For that reason, we confronted participants with typical conceptual problems in robotics and engaged them in reflective discourse, in order to help them develop personal pedagogical content knowledge as a versatile tool for use in teaching practice.

5.3.4 Course construction

In line with our theoretical framework and the assumptions mentioned above, we developed a course on teaching robotics that consisted of four three-hour sessions and various assignments to help teachers construct relevant PCK on the basis of the information given, experience, reflection and discourse when necessary. We made ample use of the insights gathered and the video recordings produced on students' conceptual development from previous research (reported in: Slangen et al., 2010). The contents of the course are outlined in Figure 5.1.

First session
The objective of the first session was to draw teachers' attention to the necessity to develop SMK, PK and PCK appropriate to the subject, i.e. robotics.
Information on types of teacher knowledge was provided. To expand teachers' SMK and PCK on the material components, the computer programming features and the concept of control, tangible Lego Mindstorms materials were provided and analysed in a combination of instruction and exploration. Teachers, analysing a problem in pairs, solved simple reason-act programming tasks, wrote and tested the program, and reflected on the effects.

Second session
The first objective of this session was to acquaint teachers with the characteristics of programming (instructions and syntax) and with conceptual thinking (function, system, control, and S-R-A). The second aim was to improve teachers' sensitivity to students' approaches, difficulties and (mis)conceptions and enhance teachers' repertoire and role in the dialogical teaching process.
Teachers in pairs practised programming, focusing on the idea that concepts are pieces of scientific and technological knowledge as well as mind tools to be used in teaching and learning. The pairs solved robotic programming problems, such as analysing a given robot and a desired functionality to convert their findings into an appropriate program, or predicting and testing a robot's operation from a program provided on the computer. The teachers were shown a video recording of students solving a robotic problem with interactive teacher support. Through manipulating tangible automatons and robots the teachers elaborated their overarching concept of 'robot' and the derived concepts (function, system, control, and S-R-A). All activities were discussed, reflected on and, through interventions of the trainer, explicitly related to conceptual learning.

Third session
The main objective of this session was to develop teachers' PCK, enabling them to use the concepts to analyse robotic problems, recognise possible difficulties students can have, and experience scaffolding techniques that may help students to overcome difficulties.
More detailed information (SMK) on the concepts and on students' conceptual development through design- and inquiry-based assignments was provided. Information on scaffolding techniques (PK) was also presented. Video recordings of interaction between a teacher and students were shown and analysed. Two robotic design problems (a soft drink vending machine and a cat rescue robot) were conducted and discussed. Additional programming instructions were offered.

Fourth session
The main objective was to improve teachers' confidence and self-efficacy with respect to the ability to develop and execute robotic problem-solving tasks in their own classes.
Teachers presented and discussed problems they themselves had designed. Some problems were selected to be solved and discussed within the group. Problem, assignment, execution and solution were reflected upon.

Figure 5.1: Outline of the course

5.3.5 Course delivery

The first author acted as the teacher educator. The course was delivered to two comparable groups of in-service teachers, a total of fifteen experienced primary school teachers (seven male and eight female, with an average of 17 years of teaching experience ranging from one to 36 years), recruited from schools in the southern province of Limburg in the Netherlands. Most of the teachers did not have experience of teaching robotics. Motives for participation by the majority of the teachers were to increase personal knowledge and skills with regard to robotics and learn how to teach robotics in school.

5.3.6 Data gathering and analysis

Data were gathered in the form of answers to semi-structured questionnaire items, mind maps and notes of the participation, and video and audio recordings of all meetings. These materials were analysed (a) to enable qualitative retrospective analysis (Cobb, Confrey, Disessa, Lehrer, & Schauble, 2003) of the participants' subject matter knowledge, pedagogical knowledge (i.e. scaffolding skills) and pedagogical content knowledge, (b) to understand the mechanisms for development of these forms of knowledge, and (c) to estimate the possibilities and limitations of teaching robotics by these teachers in their primary schools.

Questionnaires were used at the beginning and the end of the programme. Initial answers (Q1) were compared with the final answers (Q2) against the background of the conceptual framework of robotics as presented in the theory section, in order to detect change and development with regard to knowledge of robotics, knowledge of students' conceptions and ideas on effective teaching.

Mind maps drawn at the start of the first meeting (MM1) and redrawn in the last meeting (MM2) provided additional information on teacher knowledge and how teachers related various aspects of robotics to each other.

Video recordings (VR) allowed for analysis of teachers' activities and spontaneous reactions to various interventions, such as assignments and questions. Teachers' behaviour was also compared with the way students reacted to similar assignments in a previous study (Slangen et al., 2010).

Audio recordings (AR) allowed for discourse analysis. This enabled investigation of teacher understanding of the concepts and derivation of the mechanisms and characteristics of conceptual development in the context of the interventions.

Notes (N) taken by the participants were analysed for additional cues on concept development.

We used Atlas.ti to tag items in the questionnaire, notes, and audio fragments. Frequencies within the labels were used as a guide towards patterns and interpretations.

In general, we constantly compared teachers' ideas and actions with the theoretical framework. Did teachers take the relevant subject matter knowledge into account in their answers to questions, in their utterances, in their decisions?

Did teachers mention or apply scaffolding techniques whenever adequate? Labels (e.g. “uses the systems concept”) were developed and applied to data units by the first author. The second author checked the interpretations. In the case of disagreement, the original data were reinterpreted until agreement occurred.

Cues on attitudes and self-efficacy were mainly derived from the answers to the questionnaires and the discourse. We elaborated our data into preliminary texts for a member check (Silverman, 2006). Ten of the fifteen participants reacted and agreed with the texts. The main reason for non-response was lack of time, not disagreement.

5.4 Results

In this section, we report on the patterns in the teachers’ actions, reactions and utterances resulting from the instruction, assignments, and discussions during the professional development programme. We illustrate these patterns with representative examples. The abbreviations mentioned before refer to the different data sources.

5.4.1 Acquisition of subject matter knowledge

In the first session the teachers drew a mind map to visualise their knowledge about robotics and in the questionnaire teachers described what particularly characterised robotics. We analysed the mind maps and the outcome of the corresponding questions by means of classifying remarks referring to the conceptual labels (function, control, system, and S-R-A). From the mind map and the outcomes of the questionnaire we concluded that teachers’ initially predominantly characterise robotics using rather generic concepts that denote “function” (38 scores) and “control” (15 scores). The function seems to be to help humans and robots do this efficiently and accurately:

> *(Q1): To save costs in the industry. Labour that is boring doesn’t have to be done by humans anymore. Higher production with fewer people.*

Teachers, however, did not explicitly focus on the necessity to perform a functional analysis of problem and context before designing, constructing, and programming a robot.

Although the term control is explicitly mentioned in four mind maps only, the mind maps and answers on the questionnaire showed that most teachers regard robots as programmed, that is, controlled machines:

(Q1): A programmed machine or automaton that, with a simple operation, executes a task for someone.

Most teachers (12) showed in one or more of their answers on the questionnaire that learning to programme is part of what students have to learn in robotics. One teacher thought that programming was too difficult for children to learn.

The concept of systems thinking was never explicitly mentioned in the initial mind maps and questionnaire. Although a few teachers hinted at a relation between causal loop thinking and programming, just one of the teachers knew that a robot was an autonomous interactive machine controlled by sense-reason-act loops.

From the comparison of the mind maps MM1 and MM2 we saw that most teachers (11) integrated several new concepts like function, system, control, and S-R-A. Moreover, they (5) stressed the systematic problem-solving approach. From analysing fragments of the problem-solving discourse in the third session we concluded that most teachers actively used conceptual knowledge to find a solution to the given robotic problem. The concepts function and system were used more frequently than control and S-R-A. Gradually, teachers refined and elaborated on their knowledge. From the answers in the questionnaires, we can deduce that the information we intended to convey was received and elaborated upon. Most teachers (11) indicated they possessed more knowledge about the use of the concepts in relation to a robotic problem-solving process and were able to define robotics using the concepts of function (12), system (9), control (12) and sense-reason-act looping (12):

(Q2): In reality [robots] are machines that can observe, reason and act. [I learned] process thinking, problem analysis, and dividing a problem in modules. [I know about] concepts: function, system, control, and coding.

Some teachers referred to S-R-A looping by means of mentioning the causality in this process:

(Q2):[I learned about] thinking in loops, "if-then" reasoning, actuators, sensors and what they can do.

5.4.2 Acquisition of knowledge concerning students' conceptual development

During the course we discussed the way in which students can acquire an understanding of robotics in terms of the four concepts, and how they encounter and solve problems in an inquiry- and design-based setting. Several teachers (eight) initially conjectured that students would have difficulty with systematic problem analysis and with programming the robot:

> *(Q1): [Students and teachers will have difficulties] investigating and finding solutions themselves. Teachers and students are used to giving or receiving answers quickly.*

Gradually, as a result of the activities and discourse during the meetings, the teachers (10) became more aware of the possibilities of using the robotic concepts as pedagogical tools to teach students to analyse robotic problems systematically:

> *(N): The concepts are a kind of stepping-stone for teacher and student. Without using the definition of the concepts, students develop a kind of awareness of the existence of these concepts. This can be done by discourse while building and programming.*

5.4.3 Activating and elaborating pedagogical knowledge and scaffolding skills in an inquiry- and design-based setting

By the end of the course most teachers (thirteen) said in their notes that scaffolding students' thinking in their attempts to design, investigate and solve problems could be important for achieving conceptual understanding:

> *(N): Scaffold students by asking questioning, reasoning together, redirect processes, give solutions, et cetera.*

A few teachers stressed that students' self-directed learning needed to be supported:

> *(Q2): The teacher is supposed to support students with their learning process. They should not find out everything all by themselves. The learning process is determined by discoveries of the students but also by support of the teacher in instances where this is necessary.*

About half the teachers initially preferred self-directed inquiry learning, whereas the other teachers preferred mixtures of instructive introductory activities with inquiry-based learning. Although the importance of supporting this learning was stressed by most teachers (10), only a few teachers specified a generic intention to supply verbal scaffolds right from the start:

> *(Q1): Stress discovery learning. What is robotics? Build, test, evaluate, improve, et cetera. Take a role as a teacher, stay as much as possible out of sight and where needed stimulate, help, challenge.*

From the audio recordings, teachers' notes, and answers to the questionnaire, we deduced that, when commenting on video fragments, all teachers became aware of the importance of dialogic teaching and verbal scaffolding to help students construct new and refined knowledge:

> *(AR): Teacher: The students, by their way of thinking, by combining, approach a higher level. Researcher: What do you mean by that? Teacher: Two know more than one, however, you have to communicate with each other in a special way. It means listening to the other person, which stimulates the other person's thinking.*

Most teachers recognised the features and possibilities of teaching robotics by verbal scaffolding and were able to denote characteristics that were consistent with theory:

> *(AR): Summarise, challenge to reflect, paraphrase students' thinking, give information, ask guiding and open questions, stimulate thinking, stay in interaction, et cetera.*
>
> *(N): Ask questions, reason together, redirect thinking, give solutions, et cetera.*
>
> *(Q2): A way of asking questions that helps the students to clarify or solve the problem.*

A few teachers (four) also recognised that scaffolding challenged and motivated students. Three teachers reflected on the discourse on scaffolding conceptual learning as a something that made them aware and focused their attention:

> *(Q2): Especially the awakening process. It is all very abstract. Discussing this approach makes you aware.*

5.4.4 Development of pedagogical content knowledge

At the start we did not find many indications of teachers' PCK. For instance, the notion that students should learn to understand the robot as a functional system and that they might have difficulties with analysing functions and with system thinking was completely absent (MM; AR). Initially, teachers seemed to be unfamiliar with the idea of teaching for conceptual development as opposed to teaching for the correct answer or the solution of the problem, that is, building and programming a robot. Moreover, several (12) statements in the questionnaire indicated that they saw learning robotics as a generic problem-solving or discovery process involving learning to think and not as a process influenced by content-specific elements:

(Q1): Learn problem-solving thinking.

(Q1): Learn analytical thinking.

(Q1): Learn a higher level of thinking.

Confronting the teachers with exemplarily robotics problems that could be analysed and solved by using specific concepts (i.e. function, system, control and sense-reason-act) was intended to overcome this and help teachers develop flexible and detailed pedagogical content knowledge. The assignments led to better insights into the four concepts themselves.

Most teachers (Q2) showed that they knew that the concept *function* referred to actions or objectives that a robot could achieve. They showed in their handling of the assignments on the automatic drinks machine and the cat rescue robot that they were able to analyse a problem using functions and sub-functions:

(AR): Teacher1: At least [the drinking machine] has to deliver drinks. Teacher 2: It should serve drinks fully automatically. Teacher 1: Therefore, it has to be able to perceive sound. Teacher 2: So a microphone has to be built in. Teacher 1: Yes. Teacher 2: It must react to sound. Teacher 1: After delivering the drinks it should supplement the empty spaces.

The function analysis, however, remained unsystematic and shallow in most cases. Participants tended to jump to the next stage (designing or programming the robot) too early and consequently were confronted with unanticipated functionality problems:

(AR): Teacher 1: We did not take notice of […] when the touch sensor hits the floor the robot should start riding […] and our robot cannot ride. Teacher 2: Who says that the robot cannot ride? Teacher 1: We did not define that function.

Grasping the features of the *systems* concept was more difficult. At the end of the course fewer than half of the teachers characterised a system as a group of interacting, interrelated, or interdependent components that form a complex and unified whole:

> *(Q2): A system is the whole (in this case the robot) that is able to execute several functions. A system consists of more systems and is related with other systems.*

> *(Q2): [A system] can come out of very different components. Within a system is some coherence and predictability.*

When executing a robotic problem-solving task some teachers explicitly defined subsystems and others recognised relations between parts of a system:

> *(AR) Teacher 1: Then we have to go to the system. Teacher 2: Transporting system. Teacher 1: Yes. Teacher 2: And the motion sensor. Teacher 1: Perception. How we do it doesn't matter at this point; we just need a perception system.*

> *(AR) Teacher 1: Yes, but movement is also detected when the front legs pass the sensor. Teacher 2: Yes. Teacher 1: The cage should not close at that moment because the back part of the cat is still outside the cage. Teacher 2: Yes, then you rather put the bait and the sensor at the back of the cage.*

Most teachers reflected on the educational possibilities of the systems concept to support students' learning. It helps to map the complex reality in identifiable entities (part-whole thinking). Although teachers themselves experienced the importance of understanding and recognising the input and output relation between entities, none of them expressed this in the questionnaire:

> *(N): Thinking in systems and subsystems is difficult. Students are superficial and expect immediate results. The teacher has to develop a structure, present small parts, give students enough time to understand the structure.*

The essence of the *control* concept was not difficult for teachers. They were aware that all robotic actions are based on algorithmic structures that are programmed by humans into the controlling device.

To control a robot one has to decide which contextual information the robot should take into account and how the internal reasoning process should be executed to generate relevant output in terms of actions. When programming and explaining some simple programs, most teachers recognised and were able to practise basic programming principles such as linear and parallel structures, iteration, causal loops, parameters, and input and output instructions to communicate with sensors and actuators:

> *(AR): Teacher 1: If temperature…. Teacher 2: Warm, high. Teacher 1: Then catch. Teacher 2: If temperature is high then catch … Teacher 1: The robot descends. Ride and search, that is the most difficult, ride search, ride search. It should search systematically.*

The execution of the assignments revealed that most teachers relatively easily manipulated the software and designed simple programs. As with students, errors or ambiguities resulting from unfamiliarity with programming instructions and syntax were resolved by testing the program:

> *(AR): Teacher 1: Click on "unlimited", there. Teacher 2: Degrees, revolutions, seconds. If we do not know how large the area is we do not know the number of seconds. Teacher 1: But last time something was said about "unlimited". You have to interpret that in another way. It is not the same as "infinite". Teacher 2: Length of time …. Teacher 1: Yes, change that in ... Teacher 2: In 20 seconds. Teacher 1: Let's see if that has an effect. Is that all right? Teacher 2: That is all right. 30 seconds. Teacher 1: Yes. Teacher 2: Yes, but then I must change everything. That one [a "move" instruction] too.*

The *sense-reason-act* concept was initially unfamiliar. Teachers' problem-solving activities (VR) and reactions in the questionnaire showed that all of them arrived at an explicit understanding of the concept:

> *(Q2): I learned to think in sequences, the if-then way to solve problems. This stimulates problem solving and analysing students' thinking. I learned anticipating and thinking in loops.*

The teacher pairs actually used S-R-A constructions when solving problems:

> *(AR): Teacher 1: But a touch sensor is also possible. Teacher 2: Yes. Teacher 1: As soon as it touches the box then the touch sensor is pushed in …. and it has a choice.… Teacher 2: Touch sensor, is that the name? Teacher 1: If the cat touches the box... Teacher 2:… Then the switch is activated and the box moves. Teacher 1: And if the touch sensor is hit. So we need a touch sensor. The touch sensor gives a signal to the trap. Teacher 2: The trap closes.*

We noticed that sometimes the teachers used the same strategy to circumvent problems as the students did. For example, they used predetermined information instead of dynamic environmental information that had to come from sensor data:

> *(AR): The pillar… I can imagine the robot is walking against it, a hard object. Then, if you know the circumference of the pillar, you can programme in such a manner that it goes around it.*

The teachers also explicitly indicated that the concepts had become tools for teaching and learning. This we can interpret as signs of developing pedagogical content knowledge:

> *(Q2): Understanding the concepts enables the students to analyse and solve problems. It helps students to understand whole-part relations. This helps to split up the problem in modules.*

> *(Q2): This is the main subject of problem-solving thinking. Starting from the problem to think about what is expected (functions), what is needed to execute that (system) and how this can result in good control.*

> *(Q2): Because these concepts can help the teacher to let students themselves develop. Tutoring the processes becomes clearer.*

> *(Q2): By means of these four concepts someone can analyse the problem well. So you prevent missing some thinking steps when resolving the problem.*

5.4.5 Self-efficacy

From the answers on the questionnaire (Q2) we deduced that, at the end of the course, most teachers (11) also intended to use robotics in their school. Most teachers (10) clearly felt competent with regard to teaching robotics in their own classrooms in the near future. This is best expressed by the following quote:

> *Q2: I now know more about robotics and I think I am capable of coaching and supporting the students.*

Several teachers (six) were concerned about not having enough knowledge and fluency in programming to support students' programming:

> *(Q2): I developed a good basis to work with students in school. I am able to solve parts of a problem by analysing it together with the students. A stumbling block could be the coding [programming] of the robot.*

Two teachers, evidently not feeling confident, expressed some reserve about bringing robotics into school at this stage. They wanted to develop more knowledge and skills first. The need to develop more knowledge and skills, especially programming skills, is also mentioned by other teachers (six) despite their self-confidence.

Four participants suggested that learning robotics is worthwhile in itself but is also a means to achieve more generic scientific and technological goals:

Q2: Robots are a means to increase students' problem-solving capacity.

Sometimes, however, teachers doubted their ability to use this open approach in normal classroom practice, when they have to take care of twenty to thirty students. Problems were expected in quickly and correctly recognising and understanding students' problems and providing just-in-time and adequate scaffolds:

(AR): Working with small groups and having enough SMK and PCK makes immediate and adequate interventions easier. Delay in teachers' reactions or interventions can frustrate students' learning.

5.4.6 Member check

All ten respondents who reacted to the member check agreed on the preliminary text and conclusions. One respondent added that in her opinion several participants found certain topics in the course to be very difficult. Other respondents (three) also pointed to this, especially with regard to programming. Most respondents (eight) said they planned to start using robotics in school or had already started. Most teachers (nine) expressed higher self-efficacy with regard to teaching robotics.

5.5 Conclusions and discussion

In this study, a professional development course was used to prepare primary school teachers to teach robotics in an inquiry- and design-based setting. We investigated their learning processes using data from questionnaires, mind maps, discussions and observations of teachers solving robotic problems, and used qualitative measures to indicate trends. We checked our interpretations with the participants and conclude that many of the intended outcomes have been achieved and that the results can be summarised as follows.

(1) Through a professional development approach, teachers with little or no experience of robotics can be convinced that robotics is a suitable topic for primary science and technology education. (2) Teachers have learned subject matter knowledge and acquired knowledge of how students learn to solve robotic

problems in an inquiry- and design-based setting. (3) Teachers have acquired pedagogical knowledge to monitor students' progress and affect this through scaffolding. (4) Teachers have acquired experience in using robotic concepts in problem-solving contexts to anticipate students' learning difficulties in order to teach the students to solve the problem themselves. (5) In terms of the Kirkpatrick (1996) levels, teachers have learned the prerequisites for pedagogical content knowledge in classroom practice. (6) Teachers recognise that robotics contributes to technological and scientific literacy in a generic sense, in that it provides a context for problem solving and the development of higher-order cognitive skills.

We did not anticipate the anxiety with which teachers focused on programming. Apparently, for many teachers, getting stuck or making a mistake in the program is more dramatic than a flawed functional analysis or a clumsy sense-reason-act loop. This may be interpreted from the perspective of traditional instructive approaches, in which teachers are supposed to know all the answers and never make mistakes themselves. A minor flaw in the program can lead to complete failure of the robot and this may be seen as an immediate threat to teacher authority. In this respect, we did not completely succeed in preparing teachers for a design- and inquiry-based approach in which the process and the resulting conceptual development have more value than correct solutions to capstone problems.

Our claims are limited by the characteristics of our interventions. In the first place, although we claim that teachers are able to develop subject matter knowledge and pedagogical content knowledge in a professional development program, there may be other ways to achieve this that we did not investigate, e.g. through direct instruction or reading.

A second limitation is that our claim that teachers can acquire PCK is necessarily based on interpretations of actions and utterances, since PCK cannot be measured directly. We know that teachers possess the prerequisite subject matter knowledge and also possess sufficient knowledge and understanding of scaffolding (pedagogical knowledge). We also know that they are acquainted with learning problems of students and with interventions that might help students to overcome these problems. What we do not yet know is whether they put this into action when it really matters: in normal classroom practice. That will be the subject of a subsequent study.

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Chapter 6: Guided reconstruction of robotics concepts in primary education

Abstract

This article reports on a design experiment aiming at developing local theory about learning and teaching robotics in primary school. In a teaching experiment student pairs performed teacher-independent tasks in robotics in order to construct knowledge about the concepts “function”, “system”, “control” and “Sense-Reason-Act” (SRA). To deepen and broaden students’ knowledge, reflective teacher-student discourses were added. The teacher and students looked back on the past trajectory to make their discoveries and experiences explicit, and to stimulate developing conceptual understanding. We gathered data from different sources, i.e., notes from task books, transcripts from video-recorded discussions, teacher interviews, and student group interviews. These data were “condensed” in order to allow for discerning usable utterances. As the students did not reach the intended level of understanding our research question was to find answers: “Why?” Conjectures on the students’ guidebook learning and teacher-students reflective discourses were formulated and tested against the condensed dataset. This led to confirmation and refinement from which two explanatory conjectures emerged. We found confirmation for the suppositions that (1) both the teachers and the students lacked what we would call a “technological perspective”, and (2) the teachers were not well enough equipped to scaffold and support student learning, as opposed to direct instruction. We concluded that unless teachers are better prepared in terms of technological aspects and perspectives, students are not likely to construct the intended conceptual knowledge. Future research has to aim at preparing teachers better, at further improving the teaching trajectory, and at exploring the theoretical possibility for students to understand some of the more complex aspects of robotic concepts.

6.1 Introduction

It is important to prepare young people for a future that will require understanding of science and technology concepts (Malik, 2014; Rocard, 2007). In their daily life, today's children encounter many applications based on automation and robotics. Nevertheless, they are often not aware of the existence, the pervasiveness, and the impact of such technology. That is why Boeijen, Kneepkens, and Thijssen (2010) from the Dutch national testing agency Cito emphasise that it is expedient that students learn about concepts of automation as early as primary school. A few contemporary Dutch authors of school textbooks (Janssen & de Koning, 2007; ter Horst, Dannenburg, van Boxtel, & Horn, 2008) pay attention to the subject of automation and robotics. Their pedagogical approach, however, is predominantly based on fact-centred rote-learning, on the basis of reading texts and doing paper-and-pencil work. Yet, learning about automation and robotics as a practice demands the development of conceptual understanding which can best be learnt in an instructional setting where students actively explore and manipulate real robotics tools and reason about them with their peers and teacher (Slangen, van Keulen, & Gravemeijer, 2011b; Slangen, Fanchamps, & Kommers, 2008). A (robotic) tool, such as Lego Mindstorms, offers an educational environment (mind tool), where students can directly manipulate the physical materials in a Direct Manipulation Environment (DME). This is likely to foster discourse, higher-order thinking and concept development. However, implementing such a way of teaching robotics within a regular curriculum is a complex endeavour because of lack of teacher time, suitable teacher education, materials that suit the students' ages, ready-for-use lessons, and affordable robotics platforms (Mataric, Koenig, & Feil-Seifer, 2007). In general terms, it can be argued that the topic of robotics is still in its nascent state in the Dutch primary school curriculum, despite the increasing interest in ICT and programming in the primary school (Maas, 2015). This study addresses this concern: it focuses on the teaching and learning of concepts of automation and robotics in a primary school setting.

6.2 Theoretical Framework

It is generally acknowledged that learning involves the active construction of knowledge by the student, and that this requires suitable learning environments that support students in mindfully organising the core information of the domain. Such environments offer possibilities to develop and adapt concepts by using analogies, imagistic representations, thought- and material experiments, and (mathematical) analysis and reasoning (Nersessian, 2008). In anticipation of how the students' reasoning may evolve, curriculum materials have to be sequenced in such a way that they address the conceptions which the students have to develop (Driver, Leach, Scott, & Wood-Robinson, 1994; Gravemeijer, 2005). Moreover, what students learn (construct) also depends on what students bring to the situation (previous knowledge), as well as on the nature of the learning situation provided by the teacher (McGregor, 2007; Vygotsky, 1979), amongst other factors.

Contemporary learning science advocates "learning for understanding" (Bransford, Brown, & Cocking, 2004; Hiebert et al., 1997). Understanding in the domain of robotics and automation implies that students have concepts at their disposal, which they can use to describe or explain how applications of automation and robotics manifest themselves in different contexts. In a more sophisticated way, understanding implies that students are able to use their knowledge and skills to find solutions for concrete automation or robotics problems. Hence, the core aspects of learning robotics lie in developing a deep understanding of robotic concepts, and applying these in meaningful ways, in practice. Meaning-making may develop through interaction with texts; however, according to (Wells, 2002) there are more effective practices to develop understanding: such as design work, planning and carrying out experiments, surveys and other forms of empirical investigation. Here the claim is that conceptual knowledge building is fostered by the process of actively manipulating the surrounding (physical) reality. For this reason, we developed a learning trajectory with tasks that might encourage students to investigate robotics and to explore how the technology functions, by observing, manipulating, reasoning, and discussing with their peers and teachers. Such tasks may support students in (re)organising their knowledge, and building on previous knowledge. The tasks may also facilitate information processing, and deep thinking, help to make thinking processes explicit, and support use of knowledge and skills (Barak & Zadok, 2009; Johnson, 1997).

According to the findings of Johnson (1997) and Twyford and Järvinen (2000), students develop conceptual knowledge best when they are encouraged to identify and solve automation and robotics problems in realistic contexts by means of peer-based learning, and activity-based and reflective practice. Making sense of technological concepts requires gaining experience, relating and theorising through active exploration and construction, through communication and dialogic reasoning, (Tytler & Peterson, 2003; van Keulen & Sol, 2012). When students go through a self-directed and rich learning trajectory in robotics, the experiences and achieved learning outcomes are likely to be deepened by teacher modelling, coaching and scaffolding (Johnson, 1997). Moreover, students' conceptual development has to be supported by a teacher-guided sustained reflective discourse (Cobb, Boufi, McClain, & Whitenack, 1997; Hogan & Pressley, 1997; Siraj-Blatchford, 2009).

A well-known approach of supporting students in developing knowledge is the idea of "guided construction" as advocated by Mercer (1995). The basic idea is that students construct the concepts they are expected to learn in a thoughtful dialogue between teachers and students, or student-student interactions (Staarman & Mercer, 2010). The objective in our study is that the students construct the core concepts of robotics primarily by working teacher-independently on the guidebook tasks. In this approach student pairs are expected to construct knowledge mainly through reading, observing, manipulating, reasoning and discussing the robotic tools with each other. However, to be able to explicate and deepen their understandings the students have to be supported in a teacher-students dialogic process, which is based on discussing what has been experienced.

However, most teachers are unfamiliar with robotics and when teachers themselves lack knowledge and experience, they may be inclined to reduce the complexity of the tasks in order to make them more accessible (Smith, 2000), which in turn may result in shallow learning. Hence, our research objective focused on the following question: How to develop a learning trajectory that avoids superficial learning? To answer this question we developed an approach in which students were presented with a series of tasks to be executed mainly teacher-independently, which were designed to help students to come to understand robotics. We assume that this is a valid pedagogical strategy, because the tasks were designed to stimulate students to actively experiment, test, compare, analyse, reason and explain their experiences and to discuss, read, write about their reflections and elaborate their experiences into deeper understanding. We hypothesised that students who successively performed the tasks in such a trajectory would be able to develop meaningful personal constructions about robotic concepts. In order to evoke high engagement and to stimulate students' dialogue, we decided to organise students to work through this trajectory in pairs (Strom & Strom, 1999).

Even though the guidebook and robotic tools were designed to play a guiding role in supporting the students' constructions, the teacher's role was also perceived to be important (Gravemeijer, 2005). Guidance by the teacher is important to make ideas explicit, to deepen them and to align students' ideas and expressions with the language used by the wider community. Therefore, the teacher would have to discuss the tasks and the outcomes, and help students to reflect on their findings and their ideas. Building on the students' experiences, questions and remarks, the teacher would be able to guide students towards relating and theorising, i.e., deeper understandings (Driver et al., 1994; Tytler & Peterson, 2003; van Keulen & Sol, 2012).

The reflective discourse might also help the teacher to better understand how and what students have learned so far. Teachers had to be well prepared for their guiding role. In order to support the students' learning, the teachers themselves would have to possess the relevant knowledge (subject matter knowledge, pedagogical knowledge, and pedagogical content knowledge) and skills (Rohaan, 2009; Slangen, van Keulen, & Gravemeijer, 2011a).

Our conception of a reflective discourse connects to the approach of Zee and Minstrell (1997). A reflective discourse is characterised by a group discussion in which students articulate their personal thoughts, remarks and questions, and in which the teacher and other students participate through questioning or commenting in order to help students articulate their opinions and conceptions. Through reciprocal student-student and teacher-student discussions every participant attempts to understand the thinking of the other. Conducting a reflective discourse demands specific teacher competencies. A teacher has to be able to identify misunderstandings, inspire students to construct new relations, help them to broaden their ideas, support them in analysing complex problems, bring in new information, conduct questioning, scaffold students' utterances on concepts, to name but a few. Therefore, an effective teacher: (1) understands how to solve problems within a specific domain, (2) can estimate what students already know, (3) knows the competencies within students' reach, and (4) knows about their preconceptions (Hogan & Pressley, 1997; Slangen et al., 2011a). Reflective teacher interventions have to reveal what students have understood (and what not), to help them to understand coherence and relations, to connect experiences and to attempt at generalisations. Next to occasional moments of teacher support during students' self-directed learning, a teacher can purposely organise group discussions which involve the students in reflecting on the past learning trajectory. Through this, the teacher can help to make the students' knowledge, skills, and understandings explicit (Johnson, 1997; Twyford & Järvinen, 2000).

6.3 Aim of the study

This research focuses on exploring and developing a better understanding of characteristics of students' learning trajectories and of the teacher's role in conducting reflective dialogues. With this focus in mind, Dutch primary school students of 11-12 years old were taught robotics through a guided (re)construction approach, using the pedagogical means of a direct manipulation environment, a structured guidebook, and accompanied by activities carried out by pairs of students and teacher-led collective reflective discourse sessions. We studied (1) students' work in the guidebooks and (2) the teachers-orchestrated discourses. The results were intended to develop and improve a local instructional theory about teaching and learning robotics. Such a local instruction theory consists of a theory about the possible learning process, and theories about the means of supporting this learning process. The means of support encompasses the instructional activities, the tools, the classroom culture, as well as the role of the teacher (Gravemeijer & Cobb, 2006). During the retrospective analysis, however, the research goal shifted towards gaining a broader understanding of the factors that counteracted the working of the local instruction theory.

6.4 Research question and methodology

6.4.1 Design research and research question

This study started as a design research project that aimed at developing a local instruction theory for teaching robotics in primary school. Design research has particular characteristics, such as intervening in the real world (as opposed to laboratory interventions), focusing on objects and processes in a specific context, being theory-oriented and developing conjectures about student learning and the teacher's role in order to come to understand and improve the design (van den Akker, Gravemeijer, McKenney, & Nieveen, 2006). In line with these features we organised a design experiment in school and studied how, (1) the guidebook-based learning trajectory, and (2) the teacher's role in the reflective discourses played out. Our study aimed to contribute to theory on the learning of robotic concepts through guided (re)construction, by offering information for the improvement of the learning trajectory and teachers' guidance and preparation. The design differed somewhat from the typical design research format (see for instance (Cobb, Confrey, Disessa, Lehrer, & Schauble, 2003), in that we did not incorporate a series of iterative adjustments in the teaching experiment. We worked with a ready-made guidebook, which the students worked through in pairs. This work with the guidebooks was complemented with four whole group discussions. As is common in design research, the goal of the research was to come to understand how the intervention worked, and how it could be improved.

The trajectory aimed at elucidating concepts of robotics. However, with respect to several concepts our analysis showed students to have difficulties in reaching the intended goals. As a consequence thereof, our research interest shifted to the following research question: *Why did the students not reach the intended level of understanding of robotics?*

6.4.2 The implementation of the study

The study consisted of five stages which will be explained in the following paragraphs.

<u>Stage 1 Developing the learning trajectory.</u>

We developed a set of instructions and guidelines for the students that were self-directing, and initiated the activities we assumed to be necessary to provoke conceptual development and help them construct important ideas of robotics. The trajectory consisted of activities such as reading, structuring information, discussing questions and answers, watching films, analysing and explaining pre-made programs, investigating robotics behaviour, et cetera. Filmic and manipulative tools were considered powerful means for developing conceptual knowledge, as they were likely to afford students explorative behaviour and constructive learning through perception and action (Gibson, 1988). Guided by the tasks students would explore video recordings about robots, use software to program and manipulate robot models. This was expected to foster students' reasoning, and to afford the construction of robotic concepts, such as that robots have functions, are systems, can be controlled, and that their actions are determined by sensory input and program. The guidebook consisted of four chapters that each addressed one of the four robotics concepts. A fifth chapter offered students a challenge to develop a robot that could perform a specific task. The guidebook was developed by the first author/researcher who was experienced in course development. A teacher trainer colleague of the researcher reviewed the guidebook and supported the researcher with optimising information. Thereafter, two teachers examined the guidebook in advance and suggested minor improvements. One pilot run started two weeks before the other trajectories. However, this did not lead to significant modifications.

Chapter 1 of the guidebook focuses on the concept of "function", which is "… the action or purpose for which something has been designed, or that users ascribe to it" (Hacker, de Vries, & Rossouw, 2009, p. 55). It explains that function(s) of technological products or processes can be approached both from the designers' point of view as well as from the users' point of view. The guidebook supports students in taking both perspectives which implies awareness and recognition that robotics products or processes serve intentions, have internal and external functions, and are based on goal-means, part-whole, and form-function relationships (Slangen et al., 2011b).

This chapter consists of six major tasks, which focus on meaningful learning of the function concept. (1) Recognising and comprehending that robots have different external functionalities, which may be achieved through students observing, comparing and explaining certain robotic phenomena. (2) Creative thinking about a self-fantasised cleaning robot is expected to bring forward goal-means reasoning. (3) Conjecturing about what a pre-made robotic model is able to do should lead to discussions about form-function relations. (4) Testing the functionality of a control program may help students to realise that there are external and internal functionalities. (5) Virtual disassembling a specific robot in functional units and assigning tasks to these units, is meant to stimulate whole-part and means-function analysis. (6) Developing a hierarchical deduction of tasks (activities) is meant to "produce" a deep analysis with respect to external and internal functionality.

Chapter 2 is about the concept of "system", which is "(…) a group of interacting, interrelated, or interdependent components that form a complex and unified whole" (Anderson & Johnson, 1997, p. 2). Students often perceive robots as creatures that act anthropomorphically. However, the robotic system consists of tangible components (sensors, programmable logic controller, actuators etc.) and non-tangible components (processes, relationships, interactions and information flows). The learning activities help students to become aware of and recognise that the composition and operation of a robot is based on a material entity, which acts as a whole according to rules, principles, et cetera, i.e., the system. This should lead to understanding and recognition of the function of the components of the system, the composition of the system, and the processes of the system.

This chapter contains four major tasks. (1) Students discuss why a certain robot goes around on a table and turns back at the edge. Questions stimulate students to think about and discuss aspects such as sensing, deciding, acting, and how these aspects interrelate. (2) They observe the behaviour of a tangible robot and track down when and through what actions the behaviour is triggered, which aims at stimulating students to think and discuss about interaction, interrelatedness and interdependency of components of the robotic system. (3) Systematically guided by questions, they investigate the functionality of the hardware components, which is meant to focus the students on the external (visible) and internal (invisible) functionality. (4) Guided by schematically presented information and questions, students are explicitly made aware of the relation between hardware functionality and related internal processes of input, reasoning, and output. The conditional reasoning processes are made explicit.

Chapter 3 is about the concept of "control", which refers to the ability to influence the behaviour of the whole system, components of that system, or other (sub)systems. Control is executed through proxy algorithms designed and programmed by the developer. The algorithms are pre-determined instruction strands, which during execution are supplied with relevant information (input) to make decisions and also to provide relevant information (output). A controller monitors and compares pre-set values of the parameters in the system with values of the controlling variables.

This chapter consist of four major tasks. (1) Some questions in the guidebook point to the function, the working, and the origin of a program as a man-made product. (2) By systematically and sequentially performing a series of small programming tasks students explore the programming environment and the programming blocks (code). Several tasks stimulate the students to think creatively about how to program an adequate solution for a given problem. (3) Predicting and testing the working of premade programs aims at coming to understand how commands can be used creatively in combination which each other and how to solve problems.

Chapter 4 addresses the Sense-Reason-Act loop (SRA), which is the core of autonomous robots. The performance of the robot is based on a mechanism (the closed-loop control) in which the controller continuously uses feedback from a sensor (*sensing*) to set up a variable that, by means of control algorithms, is compared (*reason*) with a pre-set parameter reference value. The outcome of the comparison is subsequently used by control algorithms to trigger the actuators (*act*) until the set point of the reference value has been reached. Students are confronted with tasks and experiences meant to help them develop the SRA concept.

In this chapter two major tasks focus students' attention and help them to come to understand the core of the SRA concept. (1) The first task provides some basic information about what conditional reasoning is and how it influences the program flow of SRA. (2) By means of performing practical tasks students explore and construct and predict and test the working of the "wait-until" (wait block), "repeat-until" (repeat block), and the "if-then-else" (switch block) algorithms, with different kinds of sensors, setting signifiers and variables.

Stage 2 Preparing the teachers for their guiding role

During two or three – depending on the local possibilities – individual training sessions we informed the teachers about the goal of the experiment, the set-up of the guidebook, the supporting multimedia materials (videos and pre-made programs), and the resource materials (software, Lego Mindstorms construction materials). By means of a teacher manual we provided the teachers with relevant information about the content knowledge of the concepts, about characteristics of the reflective dialogue, and techniques to verbally scaffold students' learning. We also asked the teachers to keep up with their students by working through the guidebook themselves.

Stage 3 Conducting the teaching experiment and gathering data

In order to be able to answer our research questions, we conducted a teaching experiment in four primary schools, which were distributed over the province of Limburg in the south-east of the Netherlands. Four teachers, not familiar with teaching robotics and who had not used Lego Mindstorms before, conducted the experiment with 11 to 12-year-old students of their own classes. The experiment started in January 2012 and ended in July 2012, and in total 24 pairs of students participated.

The teacher paired the students according to their ability to work well together. Each pair had their own Lego NXT robot construction set, a guidebook, a DVD with films and pre-made programs, and a computer with the Lego Mindstorms software. They performed the tasks from the guidebook independently of the teacher. After finishing a chapter, the teacher enacted a reflective discourse. The reflection was organised as a collective group discussion with (on average) twelve students. Together the student pairs and the teacher looked back on the past chapter and reflected on the activities they had accomplished so far. All pairs finished the four chapters focusing on concept development. It was, however, not possible for all students to complete the final chapter including the design assignment before the end of the school year.

Stage 4 Gathering supplementary and triangulation data.

The researcher individually interviewed each teacher by means of a semi-structured interview and conducted a semi-structured group interview with the participating students of each school. The programs made by the students were gathered for further analysis.

Stage 5 Retrospective analysis.

In this stage the researcher condensed the dataset through clustering salient information parts. After that, a retrospective analysis was conducted on the dataset by formulating and testing conjectures.

6.4.3 Data collection and analysis

We collected data from various sources:

- students' answers and comments in their guidebooks (24),
- utterances from the reflective discourses (15),
- remarks from the semi-structured interview of teachers (4), and remarks from the class interviews (4), and
- analysis of programs produced by some of the students.

In line with the suggestions by Gravemeijer and Cobb (2006), all reflective discourses and the class interviews were video-recorded. Audio-recordings were made of the teacher interviews. All recordings were transcribed to enable analysis of the dialogues and deliberations.

Because of the extent of the raw data we decided to bring the information together into a condensed dataset first. All 24 pairs performed most of the learning trajectory's activities, which involved solving the problem tasks, discussing, making notes, and writing down answers in the guidebook. The first author clustered and evaluated these notifications with respect to students' explicit understandings of the purpose of the tasks and their approach to the task. The transcripts of the teacher-students discourses were divided into episodes. An episode is a part of the discourse, which is a discrete section of text that is internally related and can be discussed separately from previous or next sections. Utterances from such sections were interpreted with open coding in relation to the core subject of that episode. Depending on the specific concept in use, different characteristics emerged from text blocks, sentences or words. A teacher-colleague also read the texts and interpretations, and in case of disagreement the sections and coding were discussed and adjusted until there was sufficient agreement. The clustering of the utterances was deemed representative within the local setting.

When an overview of the condensed data showed that the instructional sequence was not as effective as hoped for, we conducted a secondary analysis, which is the main theme of this study. In line with the Constant Comparison Method or Grounded Theory approach (Glaser & Strauss, 1967) we subsequently used the two-step data analyses procedure as described by (Cobb & Whitenack, 1996), to identify descriptive and explanatory conjectures which can empower or mitigate assumptions. *Step one* was obtaining conjectures from the condensed dataset. We formulated conjectures about the actual learning trajectory and about the actual teacher's role. Successively, these conjectures were tested against the dataset to look for confirmations or rejections. *Step two* aimed at finding explanations for the conjectures found in step one. Here we looked for general patterns that could be turned into "causal mechanisms" (Maxwell, 2004) that might explain what happened. We identified three conjectures, which were tested against the dataset.

6.5 Findings

As mentioned before we found that the initial goals were only partly reached. As a consequence, our research interest shifted to the research question: *Why did the students not reach the intended level of understanding of robotics?*

6.5.1 Patterns emerging from the data

In the design of the learning trajectory we focused on both the teacher-independent learning trajectory of the students, and the teachers' supporting role in the reflective discourse. A perusing of the condensed dataset with respect to the different robotics concepts (see earlier) generated conjectures about the students' learning processes, as well as about teachers' guiding roles in the reflective discourses. We tested those conjectures against the condensed dataset. In the following we will present the conjectures one by one, together with the corresponding results.

Conjectures in terms of the teacher-independent learning trajectory

Conjecture 1: In terms of the concept of function, most pairs appropriated (recognised and understood) the core components relating to the function concept through exploration and discovery.

Analysing the data from this perspective, we found that most pairs perceived characteristic components of the "function" concept (function and sub function, goal and means, form and function, internal and external). All pairs appointed appropriate functions and/or sub functions to different kinds of robots. Most pairs were practically aware of the goal-means relationship *"for different tasks different robots are necessary"* and were able to mention a function and appoint an appropriate means, for instance, "*move – wheels"; "see dirt – light sensor"*. With respect to form-function aspect most pairs generated matching functions from observing a static robotic model. When the robot started operating the students recognised more (unexpected) functions, such as "*speak, demonstrate emotion, deviate"*. Most students mentioned functions that were observable (external). They also demonstrated being able to distil relevant sub functions (goals) from an overarching function and to link those goals with means, for instance *"caretaking robot, has arms, to lift and move"*. However, it is remarkable that the pairs, although most were able to appoint function and sub functions, encountered problems with a whole-part analysis. They had difficulties in producing a systematic hierarchy of activities and sub activities of a "cycling" robot. For example, a cycling robot conducts sub-tasks such as balancing, steering, and moving the pedals. In turn moving pedals demands the subtasks pressing down one leg and lifting the other, which demand next subtasks. Consequently, we refined the conjecture to the extent that most students learned about function; however, constructing the specific whole-part hierarchy was out of reach for most students.

Conjecture 2: Understanding a robot as a "system", i.e., a functional entity composed of connected and interrelated parts is within reach for the students in the context of observing robotic behaviour and manipulating concrete hardware.

Analysing the data, we found that the students were able to describe and/or explain the interrelatedness of parts and specific robotic behaviour when they experienced this in a concrete observable or manipulable situation. However, the level of accuracy and completeness in these descriptions varied. In the case of a robot that went to the edge of a table surface and halted, many pairs merely mentioned a relevant component, for instance: *"By the sensor on the front side"*.

Several pairs mentioned the sensor and an action of the sensor. *"By the sensor that watches that it does not fall from the table"*, but only a few explicitly connected the sensor with a presumed internal process: *"He has a sensor with which he can see where the drop is"*. Some other pairs referred to causality mentioning a sensory input process and an output action: *"There is a sensor aimed at the surface and if it sees a greater depth, then it stops and turns around"*. When the students were pressed to give more precise answers, however, only two pairs described the process in terms of sensing, deciding, and acting. This confirmed the conjecture that the students mainly reasoned about the observable aspects.

When students manipulated a real working robot themselves we noticed progress in their understanding. More pairs described a relation between a specific sensory function and the resulting action. Several pairs referred to a permanent state of sensing as characteristic of a sensor. A few pairs mentioned an explicit relation between sensors and the program and a few other pairs mentioned a relation between the program and acting. Many pairs showed that they had some notion of the process of receiving input, processing information and generating output. However, understanding the process as a decision process based on logical (causal) reasoning was apparently too difficult for most of them. Hence, we contend that all pairs showed some awareness of the relatedness between sensors, programmable logic controller (PLC) and actuator. However, for most students this notion was generic rather than specific. Only a few pairs showed that they understood a little more of the underlying principles of internal and external relatedness of components and processes in a robotic system. In conclusion, we found confirmation for the conjecture, and elaborating on this we can refine our conjecture adding that only a few students became more acquainted with the internal processes.

Conjecture 3: Through using a robotic Direct Manipulation Environment to perform a set of tasks, the students construct general characteristics of the concept "control" and easily develop insights into how to make a simple program perform a specific task.

The teachers observed that the pairs performing the tasks by themselves were in a flow of programming, testing and discussing. The direct feedback of the DME (Lego Mindstorms) led to students' active reasoning about their personal thoughts and choices. Depending on the outcome of the test most pairs (re)considered their ideas and adapted the program if necessary. Meanwhile, they constructed notions of the "control" concept such as the purpose of a program, that a program governs a controller and its components, that a program is a set of instructions and is manmade, that instructions rule the robotic behaviour, and that there are different kinds of instructions, parameters, and influencing values. The records the students made with respect to the working of a program demonstrated that many of them developed insights in terms of the control concept; however, they sometimes had difficulties in describing this precisely. Analysis of the performed programming tasks showed that students also knew that a program was a sequence of instructions which were conducted successively. Most pairs were able to read ready-made programs and to predict the robotic behaviour. Most pairs demonstrated that they were able to program simple linear programs by themselves. However, only a few pairs demonstrated being able to use the more complex loop algorithm in a new situation by themselves. In addition, we saw indications in students' programs that they had a shallow approach to programming. In many cases the values they inputted were imprecise, or there was a disorder in the commands used, et cetera. In general, the robotic tool that was used to support students in constructing aspects of the control concept was practically adequate. However, the programming results did not reach the quality and level of accuracy that we hoped for. So, these results partly confirm our conjecture. The conjecture has to be modified in the sense that under the given conditions most students lacked the accuracy that was necessary to make full-solution programs.

Conjecture 4: Grasping the working principles of the SRA concept through the guidebook approach was attainable for only a few students.

The SRA part of the guidebook offered the students tasks to gain concrete experiences with reasoning principles of programming based on "conditionality" and "causality". These tasks should help students to develop such understanding. Retrospectively, we analysed the students' notes with respect to four coding elements or algorithms which are represented in Lego Mindstorms in the form of iconic "blocks": the "wait block", the "loop block", the "nested loop blocks", and the "switch block", corresponding respectively to the principles of "wait until", "repeat-until", "nested repeat-until", and "if-then-else". These so-called "flow" blocks have the characteristic to intervene in the routing of a program depending on detected values and set reference values. We noticed that only a small number of students were able to explicate the principles of SRA. Ten pairs were able to express what happened with respect to the wait block in terms of "if this, then that": *"If the distance becomes less than 1.27 m, then the robot starts moving"*. With respect to the loop block we noticed the same. Nine pairs showed that they were able to formulate the principle in terms of repeat-until or if-then: *"Stop repeating, if it is more than 50"*. Only five pairs formulated how a nested "repeat-until" principle could run: *"If he hears a sound, he starts moving until he sees something, and he goes on until he collides and this carries on the entire time"*. Just three pairs showed that they were able to explain the conditionality between two strands: for instance, *"If the distance is less than 40 cm, he goes in reverse; he turns and moves until the touch sensor is pushed; if the distance is greater than 40 cm, he moves limitlessly"*. These data confirm that with the chosen approach only a small number of pairs were able to construct the principles of the SRA concept. Approximately 40% of the students (re)constructed the if-then and the repeat-until reasoning. Only 10-20% of students (re)constructed the nested loop or the if-then-else algorithm. Several pairs also produced a self-invented program. Only a few made (barely) functional or correct use of flow blocks in their program. Most students limited themselves to a linear program with direct action blocks. In conclusion, the analysis of the activities of the SRA chapter confirms the conjecture that most aspects of this concept, despite the support of the tasks, were out of reach for most students.

Summarising, the analysis of the conjectures of student learning from the several pedagogical tools leads to the conclusion that most students were able to develop generic notions of the concepts "function", "system", and "control". The students understood why robots are built differently. They understood that developing a functional robot demands form-function, goal-means and whole-part analysis. The students were generally aware that there is a relationship between a kind of internal process and hardware components, between receiving input, processing and output. The students also demonstrated an understanding that a robot is controlled by means of a sequence of instructions. In general, the initial living-being (anthropomorphic, animalistic) perspective of a robot was abandoned, but it was only partly replaced by a technological perspective. Moreover, in the spoken language this living-being perspective remained persistent. We also noticed some striking difficulties. The students were less successful when tasks were related to more abstract internal analysis and processes. The students had difficulties when invited to analyse a functional (whole-part) activity hierarchy, or to explain the decision processes based on logical (causal) reasoning, in particular when reasoning had to be based on conditionally comparing variable input with set parameters' values.

Conjectures concerning the reflective discourse

With regards to the reflective discourses we formulated two conjectures, which we tested on the condensed data.

Conjecture 5: During the reflective discourse, the teachers struggled with asking meaningful but not too directive questions, and offering meaningful but not too directive scaffolding.

To come to understand the teachers' role in complex content driven discussions, we retrospectively analysed both the process and the content of the discourse. We note that the teachers were advised to take on a supportive role in order to stimulate students to construct important aspects of the concept-in-use through reasoning and not through reproducing instructions. In order to do so, the teachers were provided with scaffolding techniques that could stimulate students to reason, such as questioning, comparing, contrasting, elaborating, arguing, perspective taking, et cetera. Data analysis showed that teachers made selective use of these techniques, they mainly asked questions. About 65% of the teachers' actions appeared to be questioning and only 35% were other scaffolding techniques. Most of the time the discourse followed the following elicitation pattern: "teacher question – student answer – teacher reaction and/or teacher question – student answer …".

Questions were used to initiate a discussion about the tasks of the robot, (sub)function or application. We noticed that teachers also asked many questions to let students elaborate or refine their reactions. Teachers often reacted by repeating an answer, hence setting up the stage for the next question. Discussions between students themselves, with the teacher in a supporting role, rarely took place. In the interviews, the teachers indicated that they were well aware of what they were supposed to do, but struggled with the enactment. "*Teacher: the students should articulate what has happened or how they think. You have to be constantly aware, how do I ask …, how do I react … , do I give …, … when children verbalise something, and I react 'so you mean ... … ?' And then I fill in how they think and that is not beneficial."* Another teacher concluded that he had difficulties asking questions, because he often asked the same kinds of questions. Or, as yet another teacher pointed out, asking the "right" question was sometimes difficult: *"Sometimes you ask and ask again; you pull and you conclude that it [understanding] is not there yet."* Or, as his colleague puts it: *"You want to get something out of those children and I do not know whether I have always succeeded."*

We may conclude that the teachers tried to ask questions aiming at deepening the students' understanding, but often without much avail. They rarely used scaffolding techniques such as comparing, contrasting, elaborating, arguing, and perspective taking, which could have helped students in constructing more profound ideas.

Conjecture 6: The teachers did not succeed in stimulating the students to think about what seemed to be most difficult, the internal functionality and activity – sub activity.

We checked this conjecture for the discourses on function, system, control, and SRA. In the following we will discuss the results for these four topics in sequence. With respect to the ***function concept***, we noticed that more than 80% of the discourse was about recalling aspects of external functionality, the goal-means relation, whole-part relation, function – sub-function, and intentionality of function. For example: "*Teacher: Why do you often use robots? …. Student: To do things which we find very difficult.*" Or: "*Teacher: He has an arm and what should it be able to do? Student: Move towards the strawberry.*" Scanning the questions, reactions, and discussion units of the discourses on the function concept made clear that the majority of the discourse was on describing, and on talking about what had been experienced, heard, seen, thought, and felt. Only very rarely did teachers pose questions or initiate discussions to stimulate students to think in a generative way about technical solutions to the problems at hand. For instance: "*Teacher: Then he chooses another route. Very well, and how can you ensure that at the end he cleaned the whole floor? Not, for instance, that he only ran up and down the same track?*" The teachers were expected to use a substantial part of the discussion to identify, clarify and deepen the technical content that had not yet been understood fully by the students (at that stage). However, little attention (15%) was directed to explicate and understand the internal functionality. We also noticed that in the discussion the internal functionality was typically approached in a generalised manner. "*Teacher: Yes, we learned that we have to program the robot to make him do something.*" All teachers seemed to have noticed that building a hierarchy of activities – sub-activities was a difficult topic. They spent substantial discourse time (25%) on this topic. The content analysis of the discussions provided a remarkable finding: despite the substantial attention all four teachers paid to hierarchies, the students only came up with observable sub-activities for the activity cycling such as "balance, steer, pedal, and observe". Only one teacher explicitly discussed (analysed) sub activities of sub activity with the students and tried to make internal processes explicit, for instance which activities are needed to pedal.

In summary, the teachers did not succeed in stimulating the students in thinking about what seemed to be difficult, namely the internal functionality and activity – sub activity.

Concerning the robotic ***system characteristics*** and the internal and hardware components all teachers discussed with their students which hardware components were important to form a working robotic system. These discussions were about relatedness of components, the dependency between parts, and adaptation of parts. We noticed, however, that these reactions were mainly formulated in general terms. The teachers seemed to be conscious that focusing the attention of the students on internal aspects was necessary for a good understanding of the "system" concept. To do so, teachers asked elaborating or deepening questions. Questions were for instance*: "Teacher: What more can be said about a sensor apart from that it perceives?"* Or: "*Teacher: A signal, which signal does it transmit?"* Or: *"Teacher: And how does the box (PLC) know what to do?"* Students demonstrated some awareness of something internal, however, their answers were general and superficial. "*Student: That is programmed, if that sees something, then it is programmed that it has to go backwards."* The students did not have precise notions of what happened internally, and at the same time they lacked a suitable verbal repertoire to precisely formulate their ideas. Moreover, the teachers themselves rarely used qualitative technical vocabulary to deepen students' understanding of the internal processes.

In summary, we may conclude that the discussions about the robotic system characteristics and the internal and hardware components were predominantly superficial and teachers rarely used the opportunities to deepen students' knowledge and understanding of the internal.

To find out how teachers and students discussed the ***control concept*** we analysed teacher-student discourses with respect to the content specific reactions and questions. Three teachers predominantly discussed the practical programming experiences in detail. The different program blocks (commands), the parameters, variables and values were recalled and discussed in a general and specific way. The teachers asked the students to verbalise how a program was made and how to adjust program blocks. The teachers focused students' attention on developing deeper understandings of the syntax of different blocks, parameters and values. These teachers explained several practical programming difficulties, for instance, misunderstandings about the adjustment of a specific parameter, such as the duration of motor activity, which in turn could be expressed in sub-parameters (seconds, rotations, degrees). Some students told the teacher that they had succeeded in making some programs of their own. One teacher asked some pairs to present their own programs, and subsequently to reconstruct and describe the chosen blocks and its parameters.

The fourth teacher focused students on a general understanding of control through statements such as "a program governs a controller and its components", "a program is a set of instructions", "instructions rule robotic behaviour". This teacher made the students aware of the interdependency between hardware functionality and the programming software. The teacher asked for a definition of programming in order to let students develop a general (theoretical) insight. *"Teacher: ...... can you explain what it means to create a program? Student: A program consists of parts you placed yourselves and which the robot then can execute. Teacher: You said it very well, parts that you placed and the robot then can execute."*

As the attention for programming was predominantly oriented on recalling the coding characteristics, most teachers did not ask pairs how they managed to solve problems, how they were sure about the quality and correctness of their programs, et cetera. They did not ask students to explain the process of developing the program, the difficulties, mistakes, the strategy used, etc. Only one teacher once explicitly asked the students how they managed to make the robot go exactly one metre. "*Teacher: … but how did you know how many seconds he had to keep going for a metre? Students: We didn't know, you try it, and from the result you get, you try again and try again. Teacher: So how did you tackle the problem? What did you do first? Student: Yes, look how many seconds we had first … Student: First we had about 5 seconds and then if the distance was too short we added 2 seconds more. Teacher: So you estimated 5 seconds to go about a metre and you found out that was too little? Student: yes or too long I don't know anymore. Student: Yes it was 5.5. Teacher: That was it exactly? Student: Yes."* These students implicitly explained their systematic strategy of estimating and adjusting. The teacher also made the other students aware of this method. This teacher supported the students by noticing and emphasising that programming is often a case of accuracy.

In short, the analysis showed that the teachers discussed either the general notions of control, or the specific coding aspects; they overlooked the need to integrate these. We may add that we also found that the teachers' manuals focused on general aspects, while the students' guidebook predominantly focused on coding instructions.

The analysis of the dialogue units of the ***SRA*** discourse on process and content characteristics provided evidence that teachers often took control of the progress of the discussions by means of asking students for experiences and examples, explanations and coherences, and sometimes by reformulating students' reactions. The teachers invited the students to retrieve experiences from the past trajectory, and discussed these predominantly without attempting to relate and to generalise. We noticed many invitations and remarks to students to describe their experiences: *"Teacher: Detect, all right, what does it detect?".* The teachers did ask about relations but not very often: *"Teacher: Does the robot compare these things?"* Sometimes the teacher reformulated relations from students' remarks. *"Teacher: So you have also programmed that if the robot collides with something it has to go backwards?"* Remarkably, the teachers seldom asked for or formulated generalising conclusions, which could have led to a more theoretical understanding of principles and rules. Only in some rare cases teachers (re)formulated students' remarks into generalising conclusions: *"So you can set up a robot … if I hear or feel this, or if I notice this then a certain action happens."*

With comments and questions teachers tried to stimulate students' meaningful reasoning about SRA related topics, for instance, how to program a sound sensor. However, such discussions often ended rather superficially. "Teacher: OK so if the sensor hears a sound you tell the robot what he has to do." With respect to the SRA concept teacher and students did give attention to aspects such as causality, conditionality, if-then decisions (wait-until, repeat-until), loops and nested loops and if-then-else decisions. However, the teachers and students predominantly focused on the aspect of "if-then" reasoning such as wait-until and repeat-until. The teacher made students, for instance, aware of the decision principles and asked them to comment on if-then and repeat-until. "Teacher: does this instruction repeat-until? Student: He carries on moving, for example, until the distance is less than 1 m and then it stops." We found only one teacher who once explicitly generalised cause and effect reasoning and focused the students' attention on the existence of the causality principle in the programming of the robot. "Now, my question to you is, were there … programming instructions which had to do with cause and effect? Student: Yes when he had to measure that he is less than 1.27 m then … that sensor sends to that box and that box knows that it has to send to the wheels that they have to stop." Another teacher tried to foster the students' understanding of the R in SRA by making the students aware of the conditionality principle. "Teacher: Yes, measure and compare. He measures and he compares. Is what I measure in accordance with what has been programmed? If so then execute that action…"

It was remarkable that the teachers never explicitly discussed the nested loop ("repeat-until the repeat-until") and the switch ("if-then-else") in the reflective discourse. Two opportunities to start a discussion about the nested loop and a switch were not taken advantage of, despite the triggers the students themselves offered. *"Student: We had a kind of program with move blocks, sound blocks, display blocks, and a loop, and that again in a loop, and we had to look what happened, and you had to fill in the right things to look how it was with that block."* Or: *"Student: … this robot measures and then there were two things, if the distance is greater than 1 m then do that and if that is less than 1 m then do something else."*

Analysis of the data showed that teachers did not initiate discussions about the nested-loop and switch block, and often missed good opportunities to steer the discussion in such a direction.

To sum up, the discussions concerning relevant principles of SRA were restricted to the simplest variant, the if-then reasoning. Conditional principles based on "nested-loops" or "if-then-else" were not addressed. The teachers did not focus on deepening understanding through relating and generalising either.

Summarising: In general, the teachers appeared to be able to stimulate students in reflecting on their experiences. All concepts ("function", "system", "control" and "SRA") were brought into discussions, albeit with different results. The teachers asked the students to recall their experiences when doing the tasks in their guidebook and tried to discuss these with respect to the conceptual knowledge involved, with an eye on deepening the students' understanding. In doing so, the teachers mainly used a questioning approach and hardly used other scaffolding techniques, such as comparing, elaborating, arguing, perspective taking, et cetera. In general, we saw question-answer cycles in which students mostly reacted in generic and shallow terms using descriptions and demonstrative pronouns. Although the students demonstrated a lack of accurate and more precise vocabulary, the teachers seldom stimulated students to formulate in a more precise manner. Moreover, teachers themselves also used superficial and general terms.

The discourses were mainly about what students already knew and not about deepening or elaborating the students' understanding. Complex themes were either superficially addressed, or not at all.

A clearly relevant theme is that of understanding the internal working of a robot. However, even though the students seemed to have little notion of the technology and processes inside a robot, analysis showed that when internal functionality was discussed at all, it was mostly discussed in generic terms. There was almost no attention for underlying products and processes. It was also remarkable that the internal logical reasoning process of SRA, which proved to be difficult for many students, was not discussed at all. Both the teachers and the students had difficulties with accurately formulating SRA processes. With respect to concepts such as "control" and "SRA" we found that most teachers predominantly discussed the actual coding in detail. They focused on talking about characteristics of the program blocks (commands), using the available parameters, variables, arguments and values. The attention was on understanding the syntax of different blocks. The teachers and students did discuss the programming of if-then decisions (wait-until, repeat-until). However, they did not initiate discussions about the nested-loop or switch-block. Only in some rare cases did a teacher make students explicitly aware of a generalisation in terms of causality, conditionality, relatedness.

6.5.2 Understanding the findings

The second step in our analysis was to find causal explanations, which could reasonably explain the findings of the earlier sections. From those findings, two general tendencies emerged. Firstly, it became clear that our expectation that students would develop a sound understanding of robotics by engaging in the activities of the guidebook was only partly realised. Secondly, we noticed that despite individual teacher preparation, the teachers led superficial discussions talking predominantly about experiences and mostly failing to clarify students' understandings of relations and generalisations of robotic technology. Elaborating on this, we came to stipulate a second set of conjectures, which we tested against the data.

Most students and teachers lacked a technological point-of-view or frame of reference. This impeded their analyses of (internal) technical parts or mechanisms.

Reviewing the above findings we conjectured that the teachers and students had a way of looking at robots that deviated from what was implicitly expected.

We may explain this difference in the following manner. The teachers and students analysed robot behaviour from a layman's perspective, analysing the tasks that have to be performed and dividing them into sub-tasks. The focus is on goals, on what the robots have to do. The expert's perspective is more technological. From a technological perspective the question is, how can I make the robot do what it has to do. Thus the focus is on the working, the construction and internal mechanisms. We may take a robot that has to ride a bicycle as an example. From a layman's perspective, sub-tasks such as balancing, steering, and moving the pedals come to the fore. From a technological perspective, the focus is on the technology that is needed to do these things; how to keep balance, how to steer, or how to move the pedals. This results in ideas about motors, gears, and hinges, but also about decision mechanisms that make everything work as intended. Our conjecture is that the students and teachers in our project were completely unfamiliar with such a technological perspective. Consequently, questions about the inner working of the robot did not come up, and core elements of robotics were not revealed.

Teachers often talked about the purpose of the robot in terms of "what" the robot was able to do and not about "how" it was able to do this. "*Teacher: You looked at what a robot can do. Can you give examples? Student: They can walk, make sounds, and even more."* Almost never did our teachers demonstrate taking a more technological perspective in order to formulate the "how", for instance, in technological terms: "The distance to an object is measured with an ultrasonic sound signal, this results in a distance value. Every fraction of a second, this value is compared with a set reference value (for instance 10 cm) of the parameter minimum distance. When the outcome of the comparison is lower than 10 the PLC closes an electronic switch. This shuts off the electricity supply to the motor, and makes the robot stop." Looking through the dataset we did not find examples of such a technological disposition. In the best cases it was more or less a mixed approach of a layman's and an engineer's perspective, however, almost always in general terms. *"Teacher: the microphone picks up the sound, and gives it to the PLC and how does the PLC know what to do? How can the PLC know what to do at the time that he picked up a sound?"* Or: *"Teacher: When does he see the strawberries? How can he see them? Student: I think he compares that with the picture he got before. Teacher: Yes, you say it looks back at the picture ….. in its memory?"* Such questions do not stimulate students to analyse robotic concepts in more specific and precise technological terms. We may conclude that the teachers and the students were not inclined to ask questions which point to technological explanations or solutions. Such questions are, for instance, how is it made, how can it function, which components are necessary, can I make it operate better, how does a robot decide, what is the effect of this command, what makes the iteration stop, how can we compare, how can I attach the motor? The teachers and students apparently lacked this technological perspective, consequently, the inner working of robots was left out of the discussion.

Because most students and teachers lacked the practical language of the field about how mechanic and electronic components function it was problematic for them to come to understand and reason about how technological products are constructed and how they work.

From the students' and the teachers' remarks and questions, we deduced that explicating internal functions and processes is difficult without having the proper vocabulary at their disposal. Sometimes there was some practical understanding but the description of the processes stayed imprecise. "*Teacher: What did you notice? Student: That there is a kind of program in which there was something with an orange line. You could pull this around the stuff he had to do. Teacher: Oh, what do you mean with an orange line? Student: Yes there was a square that was orange. You could do that around the motor and then it repeated. Teacher: All right, that orange thing was a repetition."* The student demonstrated not having the precise words or expressions and the teacher repeated without correcting or specifying. The teacher's response could have been better, for instance: "The orange thing is a program flow block instruction named Repeat Until which makes it possible to repeat a set of instructions until the condition is reached. Which kind of condition did you choose (counter, time or sensor) and what was the critical value?" Such use of proper vocabulary was seldom seen in the data. In fact, the teachers themselves did not possess generalising and specific terms like "procedure", "instruction", "command", "sense", "repeat until", "if-then-else", "motor block", "sound block", parameter, et cetera.

We may conclude that the lack of technical vocabulary hampered the process of gaining deeper insights into the working of robots.

Teachers were ill-equipped to conduct a reflective discourse.

In retrospect we question the preparation of the teachers for their supporting role. Our starting point was that within a regular primary school classroom, teachers have only limited possibilities to teach robotics. Our teachers were experienced educators but not with respect to robotics instruction. The teachers were therefore asked to study the instructional materials, and to attend two or three individual sessions in which the backgrounds were explained and questions were answered. In addition, the teachers were informed about the ins and outs of a reflective discourse. Our assumption was that the teachers' manual and the teachers' version of the guidebook, in combination with a few after school instruction sessions and the teachers' pedagogical and didactical experiences, would offer sufficient preparation. However, despite this preparation the teachers mainly conducted superficial discussions, in which they predominantly talked about the students' experiences without fostering a deeper understanding of robotic concepts. We expected the teachers to orchestrate productive classroom discussions in which the underlying concepts would be the topic of discussion. The teachers showed a growing lack of content knowledge as the lessons progressed. The concept function was easy to understand and to support. However, discussing the internal functions of a technical system was already more difficult, and discussing the technological principles of an SRA function like the switch block (if-then-else) appeared to be too difficult. Moreover, some teachers were not even aware of the difficulties. One teacher remarked*: "SRA was not too difficult. I did not get many questions about it."*

In conclusion, we may assume that the teachers lacked several competencies that we needed in the discourses. Firstly, the teachers lacked personal internalised technological knowledge of, and interest in, robotics. Secondly, the teachers were not sufficiently aware of the aims of the learning trajectory. Thirdly, the teachers were not experienced enough to easily combine an elucidation of the content with powerful pedagogical practices such as questioning techniques and scaffolding (lack of Pedagogical Content Knowledge). The assumption that the information given would be sufficient to enable the teachers to independently generate relevant questions and interactions was too optimistic.

6.6 Conclusion and discussion

The objective of this study was to acquire a better insight into the characteristics and possibilities of teaching robotic concepts within the context of a regular grade 8 classroom in a Dutch primary school with 11 to 12-year-old students. We designed a teaching experiment that was conducted in four classes in different primary schools. In each classroom, several students were grouped in pairs, who worked independently through a sequence of tasks assembled in a guidebook. After completing a chapter of this book the teachers arranged a gathering of the participating students in order to deepen their understanding through discourse. During these sessions, teacher and students reconsidered the activities and findings of the previous period in order to reconstruct and deepen their understanding of the main concepts. The work of the students, (transcriptions of) their discussions, their notes and their written answers, were clustered and evaluated with respect to the students' understanding of the purpose of the tasks, and their approach to the task. The teacher-orchestrated discourses were transcribed and subsequently divided into meaningful episodes, which were coded in respect to the core subject of that episode. These meta-data showed that the course was only partly successful, as the students did not reach the intended level of conceptual understanding, which was related to the teachers' difficulties in productively orchestrating the concept deepening discourses. We therefore shifted our attention from the course design itself to the question, what factors could explain this lack of success. For the subsequent analysis we used the two-step data analyses procedure described by Cobb and Whitenack (1996). *Step one* was obtaining conjectures from the condensed dataset. We described conjectures about the actual learning trajectory and about the teacher's role. Successively, these conjectures were tested against the dataset to look for confirmations or rejections. *Step two* aimed at finding explanations for the conjectures found in step one. These conjectures were also tested against the dataset.

We found that *the students' understanding and practical application of the robotic control process was limited to linear and simple if-then reasoning*. Students demonstrated being able to fulfil the programming tasks based on the use of simple direct instruction blocks. When the tasks became more sophisticated using sensor blocks in combination with program flow blocks based on conditional and causal reasoning, or based on directing parallel processes and feedback loops, or nested loops and if-then-else strands, we noticed that students encountered ever more difficulties. Such program blocks are complex generalisations of the integration of several aspects of logical reasoning, technological principles, parallel processes, iteration and situational influencing factors. We conclude that learning about SRA principles needs an improved design that would reconsider and give more attention to the way students come to understand the relations and generalisations of the SRA concept.

We found that *the teachers needed a better preparation to be able to conduct a concept deepening reflective discourse.* The teachers predominantly conducted superficial discussions, which contradicted our expectations and goals. In general, they showed a lack of expertise with respect to both discussing the conceptual notions of function, system, control and SRA, and an in-depth understanding of these notions through relating and theorising. As a result of practical constraints there was little time to prepare the teachers. There were no possibilities for an extended and comprehensive training such as the one developed in a previous study (Slangen et al., 2011a). Instead, the teachers were informed by the researcher in two or three individual sessions about the aim of the study, the robotic tools, the guidebook, the reflective discourse and scaffolding and questioning techniques. We found a combination of factors that we assume caused difficulties in conducting this trajectory. Using the guidebook and robotic tools was not enough to help the teachers acquire a usable overview of the relevant conceptual knowledge. In addition, the teachers did not master the interaction skills (questioning and scaffolding) necessary for stimulating reasoning at the level of relating and theorising in the discourses. The condensed information on how to orchestrate a reflective discourse was clearly too minimal to be effective.

An important factor appeared to be that the *teachers and students lacked a technological perspective.* Whereas a technological perspective would focus on the working, construction and the internal mechanisms of robots, the students and the teachers analysed robot behaviour from a layman's perspective, dividing tasks into sub-tasks with an eye on *what* the robots had to do, instead of asking *how* this might work, or how to construct the robot in such a manner that it could do what it had to do. Our data showed that the students and teachers in our project were completely unfamiliar with the technological perspective. The findings suggest that the teachers lacked a framework of reference that evokes technical questions, explanations or solutions. Moreover, they were not inclined to think about robotics from a technological perspective. This seems to have led to the teachers not asking for technical descriptions and explanations such as: How is it made, how can it function, which components are necessary, can I make it operate better? They did ask deepening questions, but these were too general to encourage the students to consider the inner workings of robots.

We realise that these findings are tied to the specific setting, the design of the course and the form of the teacher preparation. We do, however, assume that this lack of a technological perspective is typical for most primary school teachers and students.

The main objective of our study was to study the possibilities for teaching robotics in a regular school setting. The conclusions and results have to be interpreted as the outcome of a study within the specific conditions of this design experiment. This experiment was effectuated by means of students carrying out a teacher-independent series of tasks on robotics complemented with a teacher-guided dialogue on construction of understanding in discourses. It proved to be a complex endeavour, which made clear that many aspects are of influence when implementing a complex new topic. The assumption that students can learn (reconstruct) robotic concepts by means of a guidebook and concretisation materials with support of discourse appeared plausible for the easier concepts. Complex concepts like SRA were difficult to learn and would need better-designed guidebook tasks and higher-level teacher support.

An important factor that hampered the learning process appeared to be that the teachers and students lacked a technological perspective and operated from a layman's perspective instead. This finding suggests that cultivating such an interest in teachers and students is probably a prerequisite for successful instruction on robotic concepts.

In conclusion, we may argue that more research is needed on: (1) How to prepare teachers to be better able to give efficient and effective support to students' conceptual development with respect to robotics in a regular school setting. (2) How to improve the learning trajectory in order to help students learn about the internal functions and processes. (3) Whether the complex programming aspects of the SRA concept are accessible for 11 to 12-year-old students, even with an improved learning trajectory. Future research can build upon many elements of the local instruction theory that was developed in this project. A specific point of attention will need to be the issue of cultivating a technological perspective.

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Chapter 7: Conclusions and discussion

7.1 Introduction

This dissertation comprised a literature study and four empirical studies that focused on the issue of teaching robotics in primary school. These studies contributed to the central research question:

> *"How can robotics be taught and learned in the context of a regular primary school grade 6 classroom?"*

From our theoretical/literature study it became clear that more attention should be paid to the teaching of robotics in the primary school curriculum. As we have elucidated in the introductory chapter (see chapter 1), there are many different tools that can facilitate students building, programming and testing real functioning robots. Such tools model the real world by means of a physical *micro world* consisting of a collection of electromechanical components (construction materials with motors and sensors), programmable controllers, and software to program the robot by means of a computer. These tools are popular with young people as they can construct something and make it work; and hence feel like they are in charge of their own work. The students can, for example, navigate, make decisions, experience consequences, and expand on ideas.

In terms of the purpose for using such robotic tools, we identified a variety of different "categories", and associated terminologies. (1) Robotic tools are often perceived as *mind tools,* because they offer problem-solving situations, which activate students' creative and critical thinking. Essential to mind tools is that the learner interprets information and starts to reorganise his/her knowledge, which may lead to conceptual changes. (2) The robotic tools used in our empirical studies, i.e. "Techno-Logica" and "Lego Mindstorms" are said to enable students to build and model real interactive digital-electro-mechanical environments and, hence, they are sometimes classified as *Dynamic Modelling Environments*. These kinds of tools make it possible to solve problems in a manipulable digital environment, where the input and resulting output can be influenced directly. Hence, these tools are also called *Direct Manipulation Environments*. Here the focus is on the interactivity of the tool. Manipulating the input immediately results in different output, which gives feedback to the user. Those tools are also called *concretisation tools* because they make a complex digital-electro-mechanical world concretely manipulable. In this study, the terminology is aligned with the focus of our attention. The term *mind tools* is used when the focus is on activating students' thinking; the term *Direct Manipulation Environment* is used when the focus is on the interactivity (e.g. the feedback function).

Despite the fact that (as we have argued in earlier chapters) there is a need to pay more attention to robotics in the regular primary school curriculum, there is a paucity of research and knowledge about teaching and learning robotics in primary school. To map the field and to obtain a broader understanding of this topic four exploratory empirical studies were carried out. In the next section we present the results of these studies. We discuss the research questions of the four studies one by one; we describe the results and provide brief explanations. Following that, we present the main findings, together with reflections on the limitations and strengths of the individual studies. Finally, we provide directions for future research and implications for practice.

7.2 Results

7.2.1 Study 1: Supporting the development of thinking by means of ICT and concretisation tools

In the first empirical study (chapter 3) the focus was on mapping the thinking behaviour that 12 pairs of Dutch grade 6 students showed in their mutual discourse when reasoning teacher-independently about two robotic problem solving tasks. The discourses were video-recorded and analysed with a self-developed instrument based on the IOWA thinking skills and the Habits of Mind model (see chapter 3). Qualitative data were gathered, which were subsequently quantified by means of scoring the verbal utterances of the students with two checklists. Because we were interested in the extent and the nature of the thinking behaviour, we focussed on the quality and quantity of the actions taken.

Observations of students using the mind tool Techno-Logica in combination with an instructional booklet showed that the problems were challenging and initiated real problem based learning (PBL) behaviour. Observations of the problem solving behaviour revealed that the students were motivated and were eager to solve the tasks. Occasionally, to identify a breakthrough moment when they were stranded in their thinking, some support was needed – e.g. short hints, open questions, motivating comments, and positive feedback. Using robotic mind tools in a regular classroom setting appeared to be possible, but it needed a knowledgeable and "flexible" teacher who could manage to attend to individual students' problems as they were working on the problem task, whilst keeping the whole class on task.

Observations revealed that active higher-order thinking and habits of mind occurred in such learning environments. The analyses of the quantitative scores showed that there was an intensive progressive discourse with much verbal active thinking behaviour and continuous reflection. Beside this, we also observed non-verbal expressions of active thinking. Testing their programmes prompted students repeatedly to reflect, to discuss solutions, and to verify results, for example. Expert behaviour (experiential thinking) increased and became more concise during the self-instruction phase, likely as an effect of the learning process during the problem solving task.

It was possible to identify the intensity of the occurrence of the different categories and to understand the scores in the perspective of the specific type of mind tool in use and the complexity of the problem solving tasks. The analyses of the quantitative results of the different types of habits of mind and thinking skills showed considerable differences between the intensity of several categories. It can be argued that these differences can be explained as a result of the nature of the mind tool in use and the characteristics of the specific problem-solving task. For instance, testing the computer programme had much in common with the evaluating thinking skills. This task prompted the need for immediate feedback and offered unrestricted opportunities for testing. We concluded that the task was suitable for developing higher order thinking skills, especially evaluating skills. Further analyses offered some indications that students benefited from what was learned in the first task when using the same tool and a similar kind of task in a more complex problem-solving situation. Problem solving processes became more efficient and quicker.

Altogether, it can be concluded that (robotic) mind tools and problem solving tasks appear to be valuable tools of instruction for fostering problem solving skills and activating students' thinking behaviour. The results suggested that different types of mind tools and tasks activated different categories of thinking. While conducting the tasks, the students learned how to better use the software, how to analyse the problem, and how the robotic tool functioned. The conclusions led to a new research question: What can students learn from using a robotic mind tool?

7.2.2 Study 2: What students can learn from working with robotic direct manipulation environments

In the second study (chapter 4) the emphasis was on clarifying what students learned when they were manipulating robots and were solving robotic problem tasks. Supported by the researcher, six pairs of students followed several lessons on robotics in an inquiry and reconstruction based way. The lessons were video-recorded and a retrospective analysis helped finding the events and issues that were useful for understanding what the students learned from working with robotics. Indicators were distilled to describe and interpret what was happening.

The study showed that the students could use several perspectives to reason about robots – e.g. a psychological perspective, a technological perspective, a function perspective, and a controlled system perspective. The students mostly used descriptions and words that referred to a psychological, technological, and function perspective. Sometimes, the more advanced control system perspective emerged. At this point, the meaning of the technological perspective referred to students' general awareness that robots were man-made devices, consisted of technological components, and functioned according to technical processes. In a later study (see chapter 6) we revised our definition of a technological perspective: we now refer to a disposition to primarily look for technological, "how come" explanations, or "how to (do)" solutions, aiming to better comprehend how internal and external technology can function.

A further analysis of the perspectives, in combination with a literature study on designing robots, led to the determination of five important conceptual categories, which students would be expected to learn about when working with robots and solving robotic problems. Conjectures were formulated about students' understanding of these concepts and these were tested against the data set.

The students learned that robots are programmed artificial constructions, even though they regularly used humanoid characterisations and descriptions to describe or explain a robot's material characteristics and functions. Data analysis revealed that students' initial concept of a robot indeed contained such elements, but that they also knew that robots were man-made technical products. They used the technological perspective to describe robots, although they had difficulties finding the appropriate words.

The students came to understand that robots are defined by their function. Initially, expressions of a function-perspective were weak and phrased in rather generic language. We found indications that a conceptual change towards more precision proceeds along three levels: i.e., general classes of robotic purposes, contextual relations and actions, and autonomy and interactivity in relation to the dedicated function. Students attained higher conceptual levels by working on problem solving tasks that included design, construction, programming and testing.

It proved difficult for the students to perceive robots as integrated systems and to anticipate interactions between various parts of the robot. Most students in our study did not spontaneously and consciously use a system-thinking approach when designing, constructing or programming problems and tasks. The robotic DME appeared to be a useful educational tool to initiate explicit, conscious, and systematic thinking about these relations.

The students understood that robots were somehow programmed by humans but had no clear understanding of what a program really is. Students indeed had a notion about the existence of an internal program but initially had no idea what such a program looked like and how it might function. Working with the DME made them familiar with the language of programming and its purpose. And they were able to design simple Reason-Act control programs.

Coming to understand how sensory input, logical reasoning processes, and actions interact was very difficult for students. Programming a Sense-Reason-Act loop was based on the ability to analyse real world conditions and to convert these into technical solutions. Such an analysis proved to be very difficult for the students. It depended on the complexity of the problem whether they were able to convert an analysis into a program.

The cognitive and conceptual analysis of robotics we conducted allowed us to develop a frame of reference for determining students' understanding of robotics. We developed a series of instructional activities that aimed at supporting students in developing functional technological literacy with respect to how robotics was designed. By using robotic DMEs students were challenged to manipulate, reason, predict, hypothesise, analyse, and test. Students compared test results with their objectives and expectations and refined their conceptual knowledge and skills constantly. The DME helped the students to experience what a robot can do, 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. Occasionally, this teaching-learning process needed some scaffolding by the teacher, who asked questions, directed their attention, gave direction, managed frustrations, gave information if necessary, and helped them to tackle difficult problems. The hands-on activities helped students to become more competent users or practitioners of this technology. In this sense, the students developed some functional technological literacy.

7.2.3 Study 3: Preparing teachers to teach robotics in primary school

In the third study (chapter 5) we explored how experienced teachers learned how to teach robotics in an inquiry- and design-based setting. A professional development course was developed and implemented to prepare fifteen teachers recruited from primary schools in the south of the Netherlands. Their learning processes were examined to answer our main research questions. Qualitative data were obtained from questionnaires, mind maps, discussions and observations of teachers who solved robotic problems.

How did the trajectory help teachers acquire the subject matter knowledge (SMK) that was needed? Data analysis showed that teachers initially predominantly characterised robotics using rather generic concepts, and they did not focus on a functional analysis of a problem and context before designing, constructing, and programming a robot. At the end of the course teachers integrated several (new) concepts like function, system, control, and SRA in a knowledgeable way. They further explicated the systematic problem-solving approach in which they actively used conceptual knowledge to find a solution to a given robotic problem. The teachers indicated that the inquiry- and design-based approach of the course, combined with the provided information, was effective with respect to their conceptual development and the problem-solving practice. Gradually, as a result of the inquiry- and design-based setting and discourse, the teachers conceptualised how students could acquire an understanding of robotic concepts and how they could learn to solve robotic problems.

How did teachers expand on their existing pedagogical knowledge (PK) towards an approach that suited the requirements of inquiry- and design-based teaching (i.e. a scaffolding approach)? Although most teachers stressed the importance of a teacher's support while learning robotics, only a few of them indicated a general intention to supply verbal scaffolds right from the beginning. We concluded that, when commenting on video fragments, all the participating teachers became aware of the importance of dialogic teaching and verbal scaffolding to help students construct new and refined knowledge. By the end of the course, most teachers were convinced that scaffolding students' learning activities in their attempts to design, investigate, and solve problems was important for achieving conceptual understanding.

How did teachers develop pedagogical content knowledge (PCK) with respect to function, system, control, and sense-reason-act? Initially, teachers were unfamiliar with the idea of teaching for conceptual development when building and programming a robot, as opposed to teaching for the correct answer or the correct solution to the problem. Confronting the teachers with exemplary robotics problems that could be analysed and solved by using specific concepts (i.e. function, system, control, and sense-reason-act) was intended to overcome this and help teachers develop flexible and detailed pedagogical content knowledge. The assignments led to better insights into the four concepts themselves and their practical applications. The teachers explicitly indicated that the concepts had become tools for teaching and learning. We interpreted this as signs they were developing pedagogical content knowledge.

How did the professional development trajectory influence teachers' attitudes and self-efficacy with regard to teaching robotics in class? We concluded that at the end of the course most teachers intended to use robotics at their school. They felt competent with regard to teaching robotics in their own classrooms. Some teachers, however, were concerned about not having enough knowledge and fluency themselves to support students in making a computer program. Some teachers doubted their ability to use this open approach in a normal classroom setting, where they had to manage the activities of 20 to 30 students.

From what the teachers wrote down in their notebooks, we drew the following conclusions. A professional development approach can be an effective means to convince teachers with little or no experience of robotics that this is a suitable topic for primary school science and technology education. The teachers said they had acquired subject matter knowledge about robotics and pedagogical content knowledge on how students could learn to solve robotic problems in an inquiry- and design-based setting. Furthermore, they claimed to have increased their pedagogical knowledge regarding how to scaffold and monitor students' progress. They considered themselves able to anticipate students' learning difficulties, which would allow them to support students in solving problems by themselves. They recognised that robotics contributed to technological and scientific literacy in a generic sense. We realised that having subject matter knowledge, pedagogical knowledge, and pedagogical content knowledge is no guarantee that teachers will implement this in practice. We conjectured that some difficulties, with respect to quickly and correctly recognising and understanding the students' problems and providing adequate scaffolds in a normal classroom practice, were to be expected. This concern gave rise to the last study of this dissertation.

7.2.4 Study 4: Guided reconstruction of robotics concepts in primary education

In the last study (chapter 6) of this dissertation we have reported on a design-research project that aimed at developing a local instructional theory for teaching robotics in primary school. An experiment was organised with four teachers and 24 grade 6 student pairs from four primary schools in the south of the Netherlands. The local instructional theory involved (1) a predominantly guidebook-based learning trajectory on robotics and (2) teacher-orchestrated reflective discourses. The primary goal of the research was to gain a better understanding of how the intervention worked, and how it could be improved under the regular conditions of teaching and teacher professionalization. As the intended goals were only partly reached the research interest shifted to the question: Why did the students not reach the intended level of understanding of robotics? We developed six conjectures about what had happened: four conjectures concerning the teacher-independent learning trajectory; and two conjectures concerning the reflective discourse, which we tested against the available data. On the basis of this we developed three explanatory conjectures, which we also tested against the data. We will briefly discuss the conjectures and our findings.

Conjectures concerning the teacher-independent learning trajectory

In terms of the concept of a function, most pairs appropriated (recognised and understood) the core components relating to the function concept through exploration and discovery. Many of the pairs who performed this task had difficulties in producing a systematic hierarchy in terms of activities and sub activities of a “cycling robot”. Consequently, the conjecture had to be refined to the extent that most students did learn about function, but that constructing the specific whole-part hierarchy was out of reach for most of them.

Understanding a robot as a “system” – i.e. a functional entity composed of connected and interrelated parts – was within reach for the students in the context of observing robotic behaviour and manipulating concrete hardware. The students were able to describe and explain the interrelatedness of parts and specific robotic behaviour when they experienced this in a concrete observable or manipulable situation. However, most pairs had difficulties with understanding the underlying principles of the internal and external relatedness of the components and processes within a robotic system. We found confirmation for the conjecture, but had to refine our conjecture by adding that only a few students got more acquainted with the internal processes.

Through using a robotic Direct Manipulation Environment to perform a set of tasks, the students could construct the general characteristics of the concept of "control" and easily developed insights on how to make a simple program to perform a specific task. In general, the instrumentation that was used to support students in constructing aspects of the control concept was practically useful. However, the pairs' programming results did not reach the quality and level of accuracy that we had hoped for. So, these results partly confirmed our conjecture, and the conjecture had to be extended in the sense that under the given conditions most students lacked the accuracy that was necessary to make full-solution programs.

Grasping the working principles of the SRA concept through the guidebook approach was attainable for only a few students. Only a few students made functional or correct use of flow blocks in their program, applying conditional ("if ..., then ....") reasoning. Most students limited themselves to a linear program using direct action blocks. The analysis of the activities relating to the SRA concept confirmed the conjecture that most aspects of this concept, despite the support from the tasks, were still out of reach for most students.

Conjectures concerning the reflective discourse:

During the reflective discourse, the teachers struggled with asking meaningful but not too directive questions, and offering meaningful but not too directive scaffolding. The teachers tried to ask questions that were meant to stimulate the students to deepen their understanding, but often without much success. They seldom used potentially more effective scaffolding techniques such as comparing, contrasting, elaborating, arguing, and perspective taking, which could have helped students in constructing more profound ideas.

The teachers did not succeed in stimulating the students to think about what seemed to be the most difficult, the internal functionality and activity - sub activity. An important aim was to develop an understanding of the internal working of a robot. However, even though the students seemed to have little understanding of the technology and processes inside a robot, analysis showed that when the teachers discussed internal functionality at all, it was typically discussed in generic terms. The teachers lacked precise notions of what happens internally, and they lacked the suitably precise language and terminology. This lack of vocabulary was noticeable with respect to all four concepts.

In relation to the previous findings three explanatory conjectures were formulated and tested.

Explanatory conjectures

Most students and teachers lacked a technological point-of-view or frame of reference. This impeded their analyses of the (internal) technical parts or mechanisms. We concluded that teachers and students were not inclined to ask questions that focussed the attention on scientific or technological explanations or solutions. We concluded that in the reflective discourse the teachers mainly checked whether the students had executed the tasks. They helped students to describe their results and turned the reflective discourse into an effective social practice, but they were not inclined to dig deeper into the content of what the students said in order to develop an understanding in technological terms. This confirmed our conjecture that both teachers and students lacked a technological perspective, and analysed robot behaviour from a layman's perspective, focusing on what the robots had to do. From a technological perspective the focus would have been on the workings, the construction and internal mechanisms. As the teachers lacked this technological perspective, they did not support the students in developing such a perspective.

Because most students and teachers lacked the language of the field to describe how mechanic and electronic components function it was problematic for them to understand and explain how technological products were constructed and how they worked. From the students' and the teachers' remarks and questions we deduced that concretising robotic internal functions and processes was difficult without having the proper vocabulary. Occasionally, the students showed signs of practical understanding, but the ways they put their experiences and interpretations into words remained imprecise, and the teachers did not correct or elaborate on this. We concluded that the students' and teachers' lack of technical vocabulary hindered the process of developing deeper and more explicit insights into the working of the robots.

Teachers were ill-equipped to conduct a reflective discourse. This showed that the way we prepared the teachers for the teaching experiment was too limited to ensure the competency needed to combine content knowledge, scaffolding techniques, and knowledge about the learning objectives into a reflective discourse that could foster conceptual development. The teachers themselves had only little personal technical experiences with respect to robotics, and they were more at ease with direct instruction than with pedagogical approaches such as questioning and dialogic scaffolding. Their experience and focus when managing a discourse with students was rather on the social processes than on developing concepts. Hence, the assumption that the teachers would be able to acquire sufficient background knowledge to generate relevant questions and suggestions to help the students to construct conceptual understanding by themselves was too optimistic.

In conclusion, we argue that teaching robotics and developing robotics concepts in primary school might be possible but is hampered by several practical constraints. In our design experiment the students' understanding and practical application of the robotic control process remained limited to linear and simple "if-then" reasoning. Effective teaching about SRA programming principles will need an improved understanding of how students can develop an understanding of the SRA concept. The teachers apparently needed more support and professional development to be able to conduct a reflective discourse that might lead to concept development in this domain. An important factor appeared to be that the teachers and most students lacked what we called a technological perspective: a disposition to want to understand technological mechanisms and constructions. We contend that our study indicates that the students and the teachers in our project were unfamiliar with such a technological perspective. This seemed to have as a consequence that the teachers did not ask for technical descriptions and explanations, such as: "How is it made, how can it function, which components are necessary, can I make it operate better?" They did ask deepening questions, but these were too general to focus the students on the inner workings of robots.

7.3 Main findings

The objective of our studies was to expand our understanding of teaching and learning robotics in a primary school setting. Our main approach was to create empirical situations, which we could study in order to develop a deeper understanding of how knowledge can be constructed in robotic direct manipulation environments in different pedagogical settings. In this respect, we point to the following theoretical contributions.

We argue that our findings on students' thinking behaviour contribute to the theory on learning and teaching with *mind tools*. Our studies showed that a robotic direct manipulation environment could be used as a powerful tool for promoting teacher independent problem solving and active thinking. The students were provided with concrete manipulative technological tools and challenging problem tasks that could be solved in an inquiry- and design-based way. By means of these materials students were prompted to study the technological content through manipulating, discussing, and reading. They demonstrated high engagement when solving these problems. We note that the pedagogical design (problem task and DME) was in alignment with the four principles of powerful learning (Dolmans, 2012): (1) Learning is an active and constructive process through which a learner creates or restructures knowledge in a meaningful way and in interaction with others. (2) The learner has an active role in planning, monitoring, and evaluating. (3) Learning is embedded in a meaningful and authentic context in which different kinds of problems are solved. (4) Learning is based on an intense reciprocal knowledge exchange and personal and collective knowledge building in small groups. Further, the design of the problem solving tasks in this dissertation and the use of DMEs were grounded in constructionist principles (Ackermann, 2001; Papert, 1980). This implied that their learning was envisioned as a creative knowledge building process where the learners experienced, reflected, thought, and acted (Kolb & Kolb, 2009). Concrete experiences that resulted in manipulating tangible objects in the real world were the foundation for the students' observations and reflections. Ideally, these reflections would become integrated in and condensed into abstract concepts from which new implications for action would follow, which could be actively tested leading to new experiences. In this set up the DMEs were chosen with an eye towards the envisioned content and context for the learning process.

We contributed to the theory of learning and teaching robotics through the development of a useful conceptual frame of reference, useful for student learning activities and teacher teaching activities to be understood and evaluated, and lesson sequences to be designed. A cognitive analysis of the content and an analysis of the students' conceptual development made it possible to identify five concepts for the understanding of robotic phenomena – i.e., function, system, construction, control, and Sense-Reason-Act (Slangen, van Keulen, & Gravemeijer, 2011). Based on this, we developed and conducted lesson plans to help students and teachers experience and understand the applicability of these robotic concepts. For practical reasons we worked with pre-constructed robotic models, and hence concepts relating to construction such as transmission, solidity, motion, were not our focus. We realised that students, when working on robotic assignments, developed an understanding of these concepts and corresponding applicable insights. From this, we were able to develop a more expanded conceptual framework within our local situation. Students understand that robots have internal and external functions, and are designed for these functions. There are part-whole, goal-means and form-function coherences. From a system perspective, they come to understand that a robot is a group of interrelated parts designed collectively to interact in a special way to achieve a designed goal through (sensory) input, (algorithmic and technical) processes, and (actuator) output. From a control perspective, they become aware of the ability to influence the behaviour of the whole system through executing proxy algorithms (processes) designed and programmed by the developer. More specifically, this means understanding programming principles about algorithms as pre-determined instruction strands, about the succession of execution of instructions, the syntax of simple direct instructions, the role of parameters and variables, the role of iterations, simple reason-act loops, for example. From the perspective of Sense-Reason-Act, understanding pertains to interactivity based on conditionality, causal reasoning, and parallel processes. Students who understand SRA can apply rather complex programming principles such as ”if-then-else reasoning” and nested loops. This framework can be used to enhance lessons and to “measure” students’ level of understanding. As a result, we found that understanding and applying the SRA principles was very difficult for the students who participated in this research project, which contributes to our understanding about what students can learn about robotics and the programming of robots. Questions remain with respect to the limits of students’ understanding of programming more complicated programmes based on conditionality and causality, for example. The increasing interest in programming in school (Maas, 2015) indicates the importance of our findings.

Our study contributed to the knowledge about the PCK for teaching about robotics. We developed a professional development trajectory, which helped teachers to feel well prepared for their role of supporting students in solving robotic problems in an inquiry or design-based setting. This professional development trajectory was based on the second empirical study, where one researcher acted as a teacher conducting a series of instructional activities on robotics (Slangen et al., 2011) (see chapter 4). While conducting the lessons the teacher/researcher decided how to act (Kansanen & Meri, 1999) by relying on his professional frame of reference. The researcher was an experienced teacher with respect to teaching robotics, with an appropriate repertoire of pedagogical content knowledge. To develop a robust professional development trajectory, an introspective analysis of the pedagogical role of the teacher (researcher) with respect to the relations between teacher, student and content (Kansanen & Meri, 1999) was conducted. This introspection addressed the skills and the kind of knowledge teachers would have to possess to be able to support students in learning robotics. It became obvious that a well-designed professional development trajectory with respect to robotics has to focus on both conceptual knowledge building and practical skills in a preferably inquiry or design based way, supported by a teacher scaffolding. Therefore, the trajectory was developed and conducted in a "teach as you preach" manner. The professional development plan was based on: (1) informing and discussing the concepts of robotics; (2) reflecting on and discussing the practice of scaffolding (observing video fragments); (3) hands-on robotics problem solving, through conducting a function and a system analysis; and (4) learning to program concrete robots. According to the reactions of the teachers and the experiences during the execution of the lessons, the teachers seemed to be prepared well enough to support students learning robotics. In general, the trajectory addressed the teachers' need to understand concepts and practices within a specific domain to be able to ask content related questions, state comparisons, and elaborate on arguments, for example. This would also help teachers better understand students' difficulties and how to manage these in a dialogic setting, in which he or she would not give answers but try to foster student reasoning. In this manner, teachers would be able to help students transform their experiences and reflections into conceptual knowledge through a process of relating to and theorising (Driver, Leach, Scott, & Wood-Robinson, 1994; Tytler & Peterson, 2003; van Keulen & Sol, 2012)

We also contributed to the knowledge about the feasibility of teaching and learning robotics in an ecologically valid situation by exploring the possibilities and limitations of learning the concepts of robotics with limited teacher support. Conducting a lesson plan on learning and teaching robotics based on a guided reconstructive pedagogy can become fruitful only when prerequisites such as teacher preparation and guidebook content are aligned with the concepts of technological perspective taking, the interior functioning of the robot internal, and complex SRA programming. The pedagogical triangle (Kansanen & Meri, 1999) stresses the alignment of students, teachers, and content in the process of teaching and learning. From our studies we deduced several complexities with respect to each of these. To achieve strong student outcomes, teachers must integrate their knowledge on content and pedagogy effectively (PCK) (Rohaan, 2009; Shulman, 1987). This is only possible when teachers possess the knowledge and skills to identify exactly what students know and can do (Timperley, Wilson, Barrar, & Fung, 2008). Therefore, it is important that teachers develop knowledge and skills of the domain themselves. The efficacy of the guidebook developed in this study was questionable with respect to developing an understanding of the interior of the robot and of complex SRA programming.

We identified, what we have called, the ability to assume a “technological perspective” to be a significant factor in learning about robotics. The lack of a technological perspective, a technological way of looking at the world, and especially at robots, kept the teachers from focusing on technological aspects such as the inner working and construction of robots. Similarly, most students did not consider those aspects, as they also lacked a technological perspective. Hence, we contend that programs on robotics will have to invest in teachers’ and students’ predispositions towards science and technology.

7.4 Strengths and limitations

The domain of teaching and learning robotics in upper classes of Dutch primary schools has rarely been investigated. Therefore, we aimed to conduct a series of exploratory studies to map important aspects of this field. The different studies in this dissertation have their specific strengths and limitations.

In general, our findings and conclusions are limited by the characteristics of the interventions and by the local settings of the different studies. Because of the explorative nature of these studies, we searched for schools and teachers who were willing to participate. These schools and teachers could be characterised as having a positive attitude towards science and technology. The participants were cooperative with respect to meeting the demands of the research methods. Our findings and conclusions have to be understood against this background of a positive attitude towards teaching science and technology. In schools without such a background it may be difficult to introduce comparable teaching activities, and hence the results would likely be different.

In several of the studies pairs of 6^{th}-grade students participated. With respect to the selection of students, we asked the teachers to pair students who worked well together. This sometimes resulted in pairs who were not always critical towards each other, or who did not make equal contributions. In the last study we asked teachers to match students who could work well together and who were also comparable with respect to cognitive capacities.

In all the studies qualitative data sampling and analysis methods were used. The data collection contained transcribed video-recordings of the four teaching experiments, clustered descriptions of student and teacher notes relating to the various problem solving tasks, transcripts of teacher and student interviews, and robotic programming and building results. As a result of this, the data were extensive and the data analysis was time consuming. This was especially the case with respect to empirical study two and four (chapters 4 and 6), where qualitative data analysis software (Atlas.ti and MAXQDA) was used to find emerging trends. It is worth noting that the data were limited to this particular group of schools, teachers and students, and accordingly the findings are limited to the interpretation of this data.

Different pedagogical designs were used for the different explorative studies. In all the designs, teachers and/or students participated. In general, the number of participating schools, teachers, and students was small and not meant for generalisation. This means that any conclusions are limited to the sample and the local context of the study.

7.5 Some directions for future research.

We developed a professional development trajectory, which according to the teachers who took part in the professional development trajectory (chapter 5) did prepare them well for teaching robotics. Hence, in our fourth study (chapter 6) we prepared the teachers for teaching robotics; not as comprehensively as in the professional development study (chapter 5), but in a more ecologically valid way. This second group of teachers, however, appeared to have difficulty with putting the proposed pedagogy into practice. Further research on professional development aimed at preparing teachers for teaching robotics within the constraints of regular schooling would be needed to further improve the theory and practice of teaching robotics.

Teachers in the last study had difficulties with using scaffolding techniques in a reflective classroom discourse; these techniques are used in order to evoke the students' technological reasoning and problem solving skills in such a manner that it would transcend merely recalling, sharing and summarising observations from previous experiences, as a kind of social exchange practice. We found that the teachers did not have the technological disposition, or mind set, to ask the kind of questions that help students to reason about technological explanations or solutions.

The teachers' lack of a technological perspective appeared to play a limiting role here. In other words, they could not give constructive feedback to students. If robotics were to be introduced in primary schools, more research would be needed that focuses on the question of how to change teachers' propensity for taking a layman's perspective and instead get them to take a more technological perspective. This question relates to research on teachers' attitudes towards teaching science and technology (Asma, van der Molen, & van Aalderen-Smeets, 2011).

The student's guidebook and the robotic tool enabled the students to develop general insights about the concepts of robotics in a teacher independent way. However, this approach did not achieve its aim of causing the students to develop the more complex conceptual understanding of the interior functioning of a robot. With respect to the embedded pedagogical approach there were apparently limitations on how and to what extent written tasks can evoke the complex thinking skills (comparing and contrasting, prioritising, extending, speculating, et cetera) that are needed to develop such an understanding. In order to develop a better understanding of the experiences with robotics and problem-solving tasks that can help students develop understanding of the internal processes, further research is needed.

From our results we may deduce that almost all primary-school students will have considerable difficulties with comprehending and applying the SRA concept. Especially complex programming elements such as the "if-then-else" and the nested loop proved difficult to comprehend. Further research would therefore be expedient in order to develop a better understanding of what 6th-grade students are able to learn with respect to the SRA concept, and what not, and under which conditions.

In general, we argue that more research is needed to develop a local instruction theory on robotics. Future research can build upon many elements of the local instruction theory that was developed in this research project. A specific point of attention will have to be the issue of cultivating a technological perspective.

7.6 Implications for practice

In Dutch primary schools there is a growing interest in incorporating science and technology in the curriculum. The science and technology domain is vast. Dutch teachers often prove to have only superficial knowledge of topics from this domain and often do not strive to substantially deepen their personal level of expertise. Currently, there is a strong focus on teaching students how to investigate scientific questions as well as on how to engineer or design solutions to technological problems. From this point of view, the topics that are chosen seem to be merely the capstones for developing generic process skills with respect to inquiry and design. Teachers could deduce from this focus on generic skills development that there is no need for them to invest in acquiring more content knowledge with respect to science and technology.

This dissertation shows that such an approach underestimates the importance of teacher knowledge and understanding of the phenomena and artefacts chosen. If teaching robotics is seen as an important topic for primary education (Boeijen, Kneepkens, & Thijssen, 2010), teachers will need to be able to support their students' learning of robotics, and they will need to become acquainted with a technological perspective and acquire the relevant knowledge and skills. This points to a complex dilemma for the educational community. It is a choice between having large numbers of teachers being able to teach science and engineering topics but only with shallow conceptual outcomes or investing considerably in developing teacher expertise for complex topics such as robotics.

The importance of "robotics" literacy for participating in our society in this decade can hardly be overestimated (van Est & Kool, 2015; Went, Kremer, & Knotterus, 2015). Hence, we think it is important to invest in the professional development of teachers, not only to help them in developing generic skills and positive attitudes with respect to inquiry and design, but also in enabling them to help students achieve a real and applicable understanding of robotics. The studies in this dissertation offer some perspectives in this direction.

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Summary

Teaching Robotics in Primary School

Today's society requires citizens to have the knowledge and skills to participate responsibly and meaningfully in a technology-based world around them. It is generally accepted that education should actively support the development of students' technological literacy. That is why the last two decades there has been a continuous effort to improve education in Science, Technology, Engineering and Mathematics (STEM) and Information Communication Technology (ICT), starting in the curricula of primary education. Teaching robotics in primary school is often regarded as a promising approach for contributing to the objective of increasing students' technological literacy, as it combines important STEM and ICT aspects. Nowadays, students experience many robotic applications in their daily lives, as robotics is integrated in so many aspects of our society. Primary schools, however, often do not pay much attention to this subject. The aim of this research, as is described in chapter 1, was to contribute to the theory of teaching and learning robotics in the context of a regularly primary school grade 6 class*. We conducted a literature study, and four design experiments. These empirical studies were qualitative and explorative in nature, aiming to contribute to our understanding of students' and teachers' learning processes in the context of robotics.

Chapter 2 describes a literature study, which led to theoretical reflections on innovative ICT applications that might be used to stimulate primary school students' active thinking. This resulted in the construction of mind tools, which were ICT-based resources that allowed students to actively manipulate the technology. These can be employed to develop students' knowledge and their reasoning skills. Essential to mind tools is that the learner can interpret information and starts to reorganise his/her knowledge, which may lead to conceptual changes.

Several types of mind tools were identified, such as semantic organisation tools, dynamic modelling tools, information interpretation tools and conversation tools. More specifically, we focused on the dynamic modelling tool "Techno-Logic", which can be used to build interactive (robotic) physical micro worlds.

* In this dissertation we used the US grade level system to indicate the research population. Grade 6 corresponds with what is called "groep 8" in the Netherlands.

These micro worlds consist of electromechanical components (construction material with motors, sensors and a programmable logical controller) that are manipulated by software. These tools integrate creative construction of real machines and models with computer-based process control. The micro world dynamically enables students to explore physics and technology concepts, and transform their understandings into working models. The tools were expected to offer numerous opportunities for practice of problem solving, and to support the development of thinking skills and “habits of mind”. It was argued that such a micro world would invite active manipulation, and that feedback from testing the model, hypotheses development, problem analysis, and the search for causal relationships would continually, stimulate critical thinking. In this study the IOWA Integrated Thinking Model and the Habits of Mind Model were explained, in order to explore some of the applications from a socio-constructivist perspective. It appeared plausible that mind tools, such as the physical micro worlds, can be used effectively as instruments that contribute to (1) creating rich learning environments that involve students in active learning, and (2) allow instructors to gain experience with the use and effects of mind tools. However, a literature search for the use of these tools as an educational aid for developing thinking and problem solving in the context of primary school showed that there was a paucity of empirical studies on this topic.

In chapter 3 the focus was on studying the thinking behaviour that pairs of Dutch grade 6 students showed in their mutual discourse when reasoning about two robotic problem solving tasks using the mind tool Techno-Logic. The students were provided with a teacher-independent instructional booklet and two pre-fabricated micro worlds, i.e., a traffic light and a Ferris wheel. Each of these micro worlds offered the student pairs a context to solve a problem task. Through programming, discussing and testing, pairs of students progressively solved the easy problem of the traffic light and the more complex Ferris wheel problem. The micro worlds functioned as a mind tool through which students were stimulated to reason about solutions.

To collect data and gain insights into problem solving discourse, all sessions were video-recorded, transcribed and quantified with a self-developed instrument based on the IOWA thinking skills and the Habits of Mind model. From the analysis of these data it was concluded that Techno-Logic proved to be a useful mind tool for teacher-independent problem-oriented learning situations to stimulate active higher-order thinking and habits of mind. It showed that the pairs, while solving a problem task with the available tools, were engaged in intense discourse. This discourse demonstrated much (non)verbal active thinking behaviour and continuous reflection. This thinking behaviour was analysed and classified according to a developed set of categories. The analysis of the quantitative results of the different types of habits of mind and thinking skills showed considerable differences between the categories. The 18 categories were organized in four higher-order thinking skills, i.e., “analysing”, “evaluating”, “connecting” and “synthesising”. Students showed substantial more “evaluating” behaviour than “analysing”, “connecting” and “synthesising”. These differences could be explained by characteristics of the mind tool-in-use, and characteristics of the specific problem task/s. A general conclusion was that mind tools can activate thinking, and that its nature and intensity is dependent on content and context. The results suggested that different types of mind tools and tasks activated different categories of thinking. Whilst conducting the tasks, the students learned how to better use the software, how to analyse the problem, and how to apply the functions of the robotic tool. It was concluded that (robotic) mind tools and problem solving tasks offer valuable educational tools for fostering problem solving skills and activating students thinking behaviour. This led to the question what students can learn from using a robotic mind tool, which was the topic of the next research project.

Chapter 4 reports on the subsequent investigation of what grade 6 students could learn from working with a robotic mind tool. A cognitive and conceptual analysis was conducted to develop a frame of reference for determining students’ understanding of robotics. A teaching experiment was conducted to explore this subject empirically. Several student pairs followed a six-lesson program in which an experienced teacher presented the robotic problems to be solved. The lessons were conducted in a dialogic manner and student pairs were invited to inquire, discuss, compare, probe, test, reflect, et cetera. In this study the Lego Mindstorms NXT robot set was used. The tools used were found to enable students to build and model real interactive digital-electro-mechanical environments (robotic micro worlds) and, hence, they were classified as Dynamic Modelling Environments. After a period of time a change in terminology occurred, as consequence of a shifting focus from *Dynamic Modelling* Environments (DME) towards *Direct Manipulation* Environments (DME). The tools used also made it possible to solve problems in a manipulable digital environment, where the input and resulting output could be influenced directly. From such a point of view the focus was on the interactivity of the tool. Manipulating the input immediately resulted in different output, which provided feedback to the user. Hence, these tools were also called Direct Manipulation Environments.

The lessons were video-recorded, and the programming of the pairs was screen captured in combination with a picture in picture (PIP) presentation of the webcam recording of their discourse. To develop a better understanding of what students may learn, the video data were retrospectively studied using a modified version of the constant comparative (analysis) method. Fragments relevant with respect to students' understanding of robotics were identified and labelled. The data revealed that students used different perspectives to reason about robots. Four perspectives with increasing sophistication were distinguished, i.e., ‘‘psychological’’, ‘‘technological’’, ‘‘function’’, and ‘‘controlled system’’.

Lesson series were also developed and conducted to investigate students' reasoning about robotics concepts. For this a cognitive content specific literature analysis was conducted on characteristics of robotics. This led to a set of concepts, which were expected to be usable as educational objectives of teaching robotics in primary education. Four main concepts, and several sub concepts, were identified: the main concepts were "Function", "System", "Control" and "Sense-Reason-Act (SRA)", which can be explained in terms of robotics characteristics. A robot is characterised by its function/s, which means that it is built to execute certain actions (linked to previously identified problems, needs, or other challenges). A robot is a system, that is, a group of interrelated and interdependent parts designed collectively to achieve a goal. It is controlled by software designed to enable the robot to execute a series of commands in an algorithmic way, and it acts autonomously, as a result of three interacting basic capabilities, i.e., sensing, reasoning, and acting.

There was evidence that the robotic direct manipulation environment challenged pupils to manipulate, reason, predict, hypothesize, analyse and test. Through comparison and discussion the students refined their conceptual knowledge and skills, and a more functional technological language emerged under the influence of scaffolding dialogues with the teacher – this was identified as the development of technological literacy. The students learnt about robots; what robots are; what they are used for; how they function; and what robots are able to do. In this sense they became more culturally technologically literate. The study provided evidence that students have little difficulty in understanding that robots are man-made technological and functional artefacts. Developing students' understanding of the controlled system concept and the complex sense-reason-act concept appeared to be more difficult, but, it is claimed, could be fostered with problem solving tasks and support from an expert teacher. These learning processes needed scaffolding by a teacher who asked questions, focused student attention, gave direction, dealt with frustration, gave information, and helped to tackle difficult problems. Results were discussed with respect to students' developing technological literacy and the possibilities for teaching and learning in primary schools.

Chapter 5 describes a study, which investigated how to prepare teachers for implementing the intended pedagogy of teaching and learning robotics. An in-service teacher professional development course was developed, and subsequently examined with respect to developing the appropriate subject matter knowledge, pedagogical knowledge, and pedagogical content knowledge.

The course was conducted by the researcher with a group of fifteen primary school teachers. The course offered 1) subject matter knowledge on designing and programming a robot and on solving robotic problem tasks; 2) pedagogical knowledge on scaffolding robotic problem solving and analysing video recorded practices; 3) pedagogical content knowledge on how students come to understand robotic concepts and perspectives and their predispositions and difficulties when working with robotics; and 4) modelling the role of the teacher and the students in lessons on robotics problems by the course leader and by the participants, followed by discussions on those roles. The course consisted of four sessions, and supported by a guidebook containing information and tasks, robotic tools and additional materials such as supplementary texts, links to internet sites and videos.

To enable a qualitative and retrospective analysis, data were collected from several sources, such as teacher notes, questionnaires, mind maps, recorded discussions, and video-recorded observations of teachers solving robotic problems. For data analysis, quantitative and qualitative measures were used to indicate trends. The raw data were transcribed into text and imported in Atlas.ti to identify relevant text fragments, and tag them with indicative labels. The tags were totalised to conduct a summative content analysis.

Analysis revealed that a professional development approach with these teachers participating in this course resulted in: (1) teachers who were convinced that robotics was a suitable topic for primary technology education; (2) teachers who developed relevant subject matter knowledge, and acquired knowledge of how students learnt to solve robotic problems; teachers who developed pedagogical knowledge to monitor students' progress and affected this through scaffolding, and who developed pedagogical content knowledge to anticipate students' learning difficulties in order to teach the students to solve the problem autonomously; (3) teachers who experienced that robotics was a suitable context for problem solving and for the development of higher-order cognitive skills; and (4) teachers who felt competent regarding teaching robotics.

The study in chapter 6 aimed at developing a local instruction theory for teaching robotics under the conditions of regular teaching practices in primary schools. To develop better understandings of the possibilities and limitations of robotic learning environments, an experiment was organised with four teachers and 48 grade 6 students, joined together in 24 pairs. The local instruction theory involved a teacher-independent guidebook-based learning trajectory and teacher-orchestrated reflective discussions. The teacher-independent course on robotics concepts was designed on the basis of (a) the insights acquired in the first four studies; and (b) principles of guided reconstruction.

A teaching experiment was carried out, in which student pairs performed a series of tasks on the concepts of “function”, “system”, “control”, and “SRA”, respectively. After having executed the series of tasks on a given concept, a reflective discussion participating the students and the teacher followed. Prior to the effectuation of the teaching experiment the teachers were individually prepared for their role of enacting the reflective discourses. However, there were no possibilities for an extended and comprehensive training, such as the one developed in the study of chapter 4. Because of practical constraints there was little time to prepare the teachers.

The learning process was investigated by sampling and analysing data from students’ notebooks, transcripts of video-recorded discourses, and transcripts of teacher and student interviews. There is evidence that many students had difficulties understanding the non-observable internal processes of the concepts “function”, “system”, and “control”, and that only a few students could understanding the “SRA” concept. The goal of the research was to gain a better understanding of how the intervention worked, and could be improved. As the intended goals were only partly reached, the research interest shifted to a related question: Why did students not reach the intended level of understanding robotics?

Therefore, the findings were clustered by condensing the rough data and looking for patterns and explanations following a two-step method: obtaining descriptive conjectures first; and explanatory conjectures second.

Conjectures concerning the teacher-independent learning trajectory were formulated and tested against the data to describe what students were able to do. It was conjectured that students were capable of understanding and applying generic notions with respect to the concepts of "function", "system", and "control". However, students appeared to be less successful when tasks related to more abstract internal analyses and processes. Especially decision processes based on logical causal or conditional reasoning seemed to be too difficult for most students. Conjectures concerning the discourses led to the conclusion that teachers mainly used question-answer cycles to discuss students' experiences, and hardly used other scaffolding techniques to deepen students' understanding. This led to predominantly superficial discussions. Topics that were difficult to understand, such as internal processes and causal and conditional reasoning, turned out to be rarely discussed in depth.

Explaining these findings, it appeared that students' understanding of robotic control processes was limited to linear and simple if-then reasoning, and that teachers needed a better preparation to be able to conduct a deepening reflective discourse. Teachers seemed to lack the knowledge, and subject didactical knowledge that was needed to conduct a reflective discourse that could help students in developing a deeper understanding of technology. There is evidence from this study that students and teachers lacked a real technological perspective. They interpreted and analysed the robot from a layman's perspective using a social-cultural frame of reference with a focus on *what* the robot has to do and why, instead of *how* the robot was expected to do this. In this sense the robot remained a black box.

In Chapter 7 the results of the individual empirical studies were collected and interpreted. Directions for future research and practical implications were articulated.

The main objective of this dissertation was the development of deeper understandings of how knowledge can be constructed in robotic direct manipulation environments in different pedagogical settings. The studies described in this dissertation contributed to theory on learning and teaching with mind tools. The tools and pedagogical settings proved to be useful to promote active thinking and inquiry- and design-based problem solving behaviour. The pedagogical designs resulted in active and constructivist processes, in which knowledge was created, restructured, and embedded in meaningful and authentic contexts, and was based on personal and collective reciprocal knowledge exchange controlled by the learners themselves. In retrospect these characteristics proved to be in line with principles of powerful learning as described in chapter 7.

The dissertation also contributed to theory on learning and teaching robotics, showing which concepts were attainable for most students, and to which extent of understanding. These findings added to a better understanding of what students can learn from a teacher independent learning trajectory. It also became clear that an expert teacher can improve students' conceptual learning, by approaching discussions on robotics from a technological perspective instead of socio-cultural based layman's perspective. Nevertheless, there still remain questions and uncertainties with respect to the limits of students' understanding of programming based on causal and conditional reasoning.

The studies also contributed to the development of knowledge about Pedagogical Content Knowledge for teaching robotics. It became clear that a well-designed professional development trajectory on robotics has to focus on combining the conceptual content knowledge and the practical pedagogical skills that allow teachers to scaffold inquiry or design based student learning. Experiencing a teaching trajectory comparable to the way they were expected to teach helped teachers to understand students' difficulties and contributed to their understanding of how to overcome these difficulties in a dialogic way.

In the studies of this thesis we varied the quality of support of the pupils' learning process. This varied from support by an expert teacher to teacher-independent learning. In the same way there was variation in intensity and comprehensiveness of teacher professionalization. It can be said that successful education in robotics concepts can in principle be achieved with a combination of rather intensive professional development and expert teacher support. From our studies we assume that teachers can be enabled for this expert role. The current educational conditions, however, are too limited to implement teaching robotics and expect expert performance and high quality outcomes. The last study offered some points of action to improve on this.

Finally, this dissertation contributed to the knowledge of the feasibility of teaching and learning robotics in an ecologically valid situation, i.e., a regular grade-6 classroom environment. In Dutch primary education there is a growing interest in introducing robotics. However, most Dutch primary school teachers are not acquainted with this theme. The results of the ecologically valid research suggest that a series of lessons on learning robotics based on a guided reconstructive pedagogy can only be productive, when teacher preparation and guidebook content are in line with a technological perspective, and take up concepts related to the interior functioning of the robot, and complex SRA programming.

The ability to take a “technological perspective” was identified to be a significant factor in teaching and learning about robotics. It seemed to depend to a large extent on the apparent absence of technological discourse (arguably linked to particular ways of looking at the world), and especially of “robotic discourse”, which kept teachers and many students back from opening black-box aspects, such as the inner functioning and construction of robots.

The studies in this dissertation were explorative in nature and have brought forward new directions for research. It is concluded that future research needs to invest in studying teachers’ predispositions towards science and technology, their scaffolding abilities in the context of students solving technological problems, and the conditions that help students to develop the SRA concept in such a way that they will be able to apply their understanding to robotic problems.

Samenvatting

Robotica onderwijzen in de basisschool

De hedendaagse samenleving heeft burgers nodig die beschikken over de kennis en vaardigheden die nodig zijn om verantwoordelijk en op een zinvolle wijze deel te nemen aan de op technologie gebaseerde wereld om hen heen. Het is daarom algemeen aanvaard dat onderwijs op een actieve wijze de ontwikkeling van technologische geletterdheid van leerlingen moet ondersteunen. Voortvloeiend hieruit is er de afgelopen twee decennia een continue inspanning geleverd om, al beginnend in de leerplannen van het basisonderwijs, het onderwijs in wetenschap & technologie (STEM)* en in informatie- en communicatietechnologie (ICT) te verbeteren. Omdat onderwijs in robotica belangrijke aspecten van zowel wetenschap & technologie als van ICT combineert wordt dit vaak beschouwd als een veelbelovende aanpak die bijdraagt aan het doel om de technologische geletterdheid van de leerlingen te vergroten. Leerlingen ervaren overigens in hun dagelijks leven al veel van die robottoepassingen aangezien robotica tegenwoordig al in veel facetten van onze maatschappij is geïntegreerd. Basisscholen besteden echter meestal niet veel aandacht aan dit onderwerp. Het doel van dit onderzoek, zoals is beschreven in hoofdstuk 1, was het leveren van een bijdrage aan de theorie van onderwijzen en leren van robotica in de context van het onderwijs in een reguliere basisschool groep 8. Daarvoor hebben wij een literatuurstudie en vier ontwerp-experimenten uitgevoerd. Deze empirische studies waren kwalitatief en exploratief van aard, met als doel bij te dragen aan onze kennis over leerprocessen van leerlingen en onderwijzers in de context van robotica.

Hoofdstuk 2 beschrijft een literatuurstudie die leidde tot theoretische reflecties over innovatieve ICT toepassingen die mogelijk ingezet kunnen worden om het actief denken van basisschool leerlingen te stimuleren. Deze studie resulteerde in het construct mind tools, hetgeen overwegend op ICT gebaseerde toepassingen zijn die leerlingen de mogelijkheid bieden actief te manipuleren met technologie en die kunnen worden ingezet om hun kennis hierover en hun redeneervaardigheid te verbeteren. Essentieel voor mind tools is dat de lerende

* In het Nederlandse onderwijs wordt meestal gesproken over wetenschap & technologie waar in het Engelstalige gebied verwezen wordt naar STEM onderwijs, omvattende Science, Technology, Engineering en Math. In de Nederlandse samenvatting van deze dissertatie houden we de term wetenschap & technologie aan, implicerend STEM onderwijs.

informatie interpreteert en start met zijn/haar kennis te reorganiseren, hetgeen kan leiden tot conceptuele ontwikkeling.

Verschillende typen mind tools werden onderscheiden, zoals de semantische organisatie-toepassingen, dynamische modelleer-toepassingen, informatie interpretatie-toepassingen en de conversatie-toepassingen. Meer specifiek, hebben we ons gericht op de dynamische modelleer toepassing "Techno-Logic", die gebruikt kan worden voor het bouwen van interactieve concrete micro-werelden, zoals bijvoorbeeld een robot. Deze micro-werelden bestaan uit elektromechanische componenten (constructie materiaal met motoren, sensoren en een programmeerbare logische controller) die worden bediend via software. Deze toepassingen integreren het creatief construeren van "echte" machines en modellen met een computergestuurde procesregeling. De micro-wereld biedt leerlingen de mogelijkheid om op een dynamische wijze fysische en technologische concepten te exploreren en hun inzichten te transformeren in werkende modellen. Van de toepassingen wordt verwacht dat ze veel kansen bieden om praktisch te oefenen met probleem oplossen en zo de ontwikkeling van denkvaardigheden en denkgewoonten ("Habits of Mind")* ondersteunen. Er wordt beargumenteerd dat een dergelijk micro wereld uitnodigt tot actief manipuleren, en dat feedback van het testen van het model, het ontwikkelen van hypotheses, het analyseren van problemen en het zoeken naar causale verbanden, het kritisch denken zou stimuleren. In deze studie worden het "IOWA Integrated Thinking Model" en het "Habits of Mind Model" uitgelegd om enkele van de toepassingen van mind tools vanuit een sociaal-constructivistisch perspectief te exploreren. Het bleek aannemelijk dat mind tools zoals de fysische micro werelden effectief kunnen worden ingezet als instrumenten die bijdragen aan (1) het creëren van rijke leeromgevingen die leerlingen betrekken in actief leren, en (2) die leerkrachten ervaring laten op doen met het gebruik en de effecten van mind tools. Echter, uit een literatuurscan bleek dat er slechts een gering aantal empirische studies gericht was op het gebruik van toepassingen van mind tools als onderwijskundig gereedschap voor het ontwikkelen van denken en probleem oplossen in de context van het basisonderwijs.

In hoofdstuk 3 lag de nadruk op het bestuderen van het denkgedrag dat leerling tweetallen uit een Nederlandse groep 8 vertoonden tijdens hun onderling discours terwijl ze – gebruikmakend van de mind tool Techno-Logic – redeneerden over twee robotica probleemoplossingstaken. De leerlingen waren voorzien van een

* De Engelse term "Habits of Mind" verwijst naar specifieke denkstrategieën die als gewoonte toegepast worden. Wij gebruiken in deze samenvatting de Nederlandstalige term denkgewoonte.

leerkracht-onafhankelijk instructieboekje en twee voorgefabriceerde micro-werelden, te weten een verkeerslicht situatie en een reuzenrad. Elk van deze micro-werelden bood de leerlingen een context voor het oplossen van een probleem. Via het programmeren, discussiëren en testen losten de leerlingen geleidelijk aan het eenvoudige probleem van de verkeerslichten, en het complexere reuzenrad probleem, op. De micro-werelden fungeerden als mind tools waarmee leerlingen werden gestimuleerd om te redeneren en argumenteren over oplossingen.

Om gegevens te verzamelen en inzicht te krijgen in het probleemoplossing discours zijn van alle sessies video opnames gemaakt, getranscribeerd en gekwantificeerd met een zelf ontwikkeld instrument dat gebaseerd was op het “IOWA thinking skills” en het “Habits of Mind” model. Er bleek dat de tweetallen een intensief discours onderhielden terwijl ze met de beschikbare toepassingen het probleem oplosten. Uit de analyse van deze gegevens werd geconcludeerd dat Techno-Logic een bruikbare mind tool was om in leerkracht-onafhankelijk probleemsituaties actief hoger-orde denken en denkgewoonten te stimuleren. Het discours toonde veel (non)verbaal actief denkgedrag en een voortdurende reflectie. Het denken werd geanalyseerd en geclassificeerd overeenkomstig een ontwikkeld set categorieën. De analyse van de kwantitatieve resultaten van de verschillende typen denkvaardigheden en denkgewoonten toonden aanzienlijke verschillen tussen de diverse categorieën. De 18 categorieën werden geclusterd in vier categorieën hoger-orde denkvaardigheden, te weten "analyseren", "evalueren", "verbinden" en "synthetiseren". Leerlingen bleken aanmerkelijk meer te "evalueren" dan te "analyseren", "verbinden" en "synthetiseren". Deze verschillen werden verklaard vanuit karakteristieken van de gebruikte mind tool en de kenmerken van het specifieke probleem. Een algemene conclusie was dat mind tools denken activeren en dat aard en intensiteit afhankelijk is van inhoud en context. De resultaten suggereren dat verschillende soorten mind tools en taken verschillende categorieën van denken activeren. Tijdens de uitvoering van de taken, hebben de leerlingen geleerd hoe de software beter te gebruiken, hoe het probleem te analyseren, en hoe de functies van de robotica toe te passen. Er werd geconcludeerd dat mind tools en probleemoplossende taken waardevolle educatieve hulpmiddelen bieden ter bevordering van probleemoplossende vaardigheden en het activeren van het denkgedrag van leerlingen. Dit leidde tot de vraag wat leerlingen kunnen leren met behulp van een robotica mind tool, hetgeen het onderwerp van het volgende onderzoeksproject werd.

Hoofdstuk 4 rapporteert over het opvolgende onderzoek dat nader onderzocht wat groep 8 leerlingen kunnen leren van het werken met een robotica mind tool. Een cognitieve en conceptuele analyse is uitgevoerd om een referentiekader te ontwikkelen voor het bepalen welke inzichten leerlingen in robotica hebben. Om dit onderwerp empirisch te exploreren is een onderwijs experiment uitgevoerd. Enkele leerling tweetallen hebben een programma bestaande uit zes lessen gevolgd, waarbinnen een ervaren leerkracht (onderzoeker) de leerlingen robot problemen aanbood om op te lossen. De lessen verliepen op een dialogische wijze waarbij de tweetallen door de leerkracht werden uitgenodigd om te onderzoeken, discussiëren, vergelijken, testen, reflecteren, et cetera. In dit onderzoek werd gebruik gemaakt van de Lego Mindstorms NXT robot. De gebruikte middelen maakten het mogelijk dat de leerlingen echte interactieve digitale elektromechanische omgevingen (robotica micro werelden) bouwden en modelleerden. Daarom werden deze mind tools ook wel geclassificeerd als Dynamische Modelleer Omgevingen (DME). Na verloop van tijd is er een verandering in terminologie opgetreden als gevolg van een accent verschuiving van de focus op dynamische modelleer omgevingen (DME) naar aandacht voor directe manipulatie omgevingen (DME). De gebruikte mind tools maakten het namelijk tevens mogelijk om problemen op te lossen in een manipuleerbare digitale omgeving, waar de invoer en de resulterende uitvoer direct kunnen worden beïnvloed. Vanuit een dergelijk perspectief ligt de focus op de interactiviteit van de toepassing. Het manipuleren van de invoer resulteert direct in andere uitvoer en geeft de gebruiker onmiddellijk feedback. Vandaar dat deze toepassingen ook wel directe manipulatie omgevingen worden genoemd.

De lessen werden met behulp van video opgenomen. Het programmeren op de computer van ieder tweetal en hun dialoog daarbij is vastgelegd via screen-capturing in combinatie met een picture in picture (PIP) presentatie van de webcam die het discours van het tweetal registreerde. Om een beter begrip te krijgen van wat leerlingen kunnen leren zijn de videogegevens retrospectief via een kwalitatieve analyse. bestudeerd, waarvoor een aangepaste versie van de “Constant Comparative Method” werd gebruikt. Fragmenten relevant met betrekking tot inzichten, die leerlingen in robotica hebben, werden geïdentificeerd en geëtiketteerd. De gegevens maakten duidelijk dat leerlingen verschillende perspectieven gebruikten om te redeneren over robots. Vier perspectieven met een toenemende complexiteit werden onderscheiden, namelijk "psychologische", "technologische", "functionele" en "bestuurd systeem".

De lessenserie werd ook ontwikkeld en uitgevoerd om te onderzoeken hoe leerlingen redeneren met betrekking tot robotica concepten. Hiervoor is een inhouds-specifieke cognitieve literatuur analyse uitgevoerd naar kenmerken van robotica. Dit leidde tot een set concepten waarvan werd verwacht dat ze bruikbaar waren als educatieve doelstellingen voor robotica onderwijs in de basisschool. Vier hoofd-concepten en diverse sub-concepten werden geïdentificeerd. Deze hoofd-concepten werden gelabeld als "Functie", "Systeem", "Besturing" en "Sense-Reason-Act (SRA)" en kunnen verklaard worden met beschrijvende termen van karakteristieken van robotica. Een robot wordt gekenmerkt door zijn functie(s), hetgeen betekent dat deze is gebouwd om bepaalde acties uit te voeren (die samenhangen met eerder geïdentificeerde problemen, behoeften, of andere uitdagingen). Een robot is een systeem, dat wil zeggen een groep van onderling verbonden en van elkaar afhankelijke onderdelen, ontworpen om collectief een doel te bereiken. De robot wordt bestuurd door software die ontwikkeld is om deze een reeks van opdrachten op een algoritmische wijze te laten uitvoeren en de robot gedraagt zich autonoom als resultaat van drie interacterende basiscapaciteiten, te weten waarnemen, redeneren en handelen (sense-reason-act).

Er was bewijs dat een robotica directe manipulatie omgeving de leerlingen uitdaagde om te manipuleren, redeneren, voorspellen, veronderstellen, analyseren en testen. Via vergelijken en bespreken verfijnden de leerlingen hun conceptuele kennis en vaardigheden en ontwikkelden ze een meer functionele technologische taal onder invloed van scaffolding dialogen met de leerkracht, hetgeen geduid werd als ontwikkeling van technologische geletterdheid. De leerlingen leerden over robots, wat robots zijn, waarvoor ze gebruikt worden, hoe ze functioneren en wat robots kunnen, en werden in die zin meer cultureel technologisch geletterd. De studie leverde bewijs dat leerlingen weinig problemen hebben met het begrijpen dat robots door mensen gemaakte technologische en functionele artefacten zijn. De leerlingen inzicht laten ontwikkelen in het concept van een bestuurd systeem en het complexe sense-reason-act concept bleek moeilijker, maar er werd geconstateerd dat leerlingen hierin vooruit geholpen konden worden met behulp van probleemoplossende taken en door ondersteuning van een deskundige leerkracht. Deze leerprocessen vereisten scaffolding door een leerkracht die vragen stelde, de aandacht van de leerling focuste, richting gaf, wist om te gaan met frustratie, informatie gaf, en hielp lastige problemen te tackelen. De resultaten worden ten slotte geplaatst in het perspectief de ontwikkelende technologische geletterdheid van leerlingen en de mogelijkheden tot het onderwijzen en leren hiervan in het basisonderwijs.

Hoofdstuk 5 beschrijft een studie die onderzocht hoe leerkrachten voorbereid kunnen worden op de uitvoering van de beoogde didactiek van onderwijzen en leren van robotica. Er is een professionaliseringstraject voor leerkrachten ontwikkeld en vervolgens getest met betrekking tot het ontwikkelen van de gewenste inhoudelijke, didactische en vakdidactische kennis.

De professionalisering werd uitgevoerd door de onderzoeker met een groep van 15 leerkrachten basisonderwijs. De cursus bood 1) inhoudelijke kennis over het ontwerpen en programmeren van een robot en het oplossen van robotica opdrachten; 2) didactische kennis over het scaffolden van het oplossen van robotica problemen en het analyseren van lespraktijken via video-opnames; 3) vakdidactische kennis over hoe leerlingen robotica concepten en perspectieven gaan begrijpen en over hun aanleg voor, en moeilijkheden met, het werken met robotica; 4) het door de cursusleider aan de deelnemers modelmatig demonstreren van de rol van de leerkracht en de leerlingen in lessen over robotica problemen gevolgd door het bespreken van deze rollen. De cursus bestond uit vier bijeenkomsten, die werden ondersteund met een instructieboekje met informatie en taken, met robot hulpmiddelen en met aanvullende materialen zoals extra teksten, links naar internetsites en video's.

Om een kwalitatieve en retrospectieve analyse mogelijk te maken werden gegevens vanuit verschillende bronnen verzameld zoals: aantekeningen, vragenlijsten, mind maps, opgenomen gesprekken en observaties uit video-opnames van leerkrachten die robotica problemen oplossen. Bij de analyse van de gegevens werden kwantitatieve en kwalitatieve middelen gebruikt om trends aan te wijzen. De ruwe gegevens werden omgezet in tekst en geïmporteerd in Atlas.ti om relevante tekstfragmenten te identificeren en indicatieve labels toe te wijzen. De labels werden getotaliseerd om een summatieve inhoudsanalyse te kunnen uitvoeren.

Uit de analyse bleek dat de professionaliseringsaanpak van deze cursus erin resulteerde dat leerkrachten: (1) inzagen dat robotica een geschikt onderwerp is voor technologie activiteiten in het basisonderwijs; (2) relevante inhoudelijke kennis ontwikkelden en kennis verwierven over hoe leerlingen robotica problemen oplossen, relevante didactische kennis ontwikkelden om de voortgang van hun leerlingen te monitoren en dit te beïnvloeden door gerichte ondersteuning, vakdidactische kennis ontwikkelden om te anticiperen op de leermoeilijkheden van de leerlingen met de intentie de leerlingen te leren zelfstandig de problemen op te lossen; (3) ervoeren dat robotica een geschikte context is voor het oplossen van problemen en het ontwikkelen van hoger-orde cognitieve vaardigheden; (4) zich competent voelden om robotica te onderwijzen.

De studie in hoofdstuk 6 was gericht op het ontwikkelen van een lokale instructie theorie voor het onderwijzen van robotica onder de condities van de reguliere praktijk in het basisonderwijs. Om beter inzicht te krijgen in de mogelijkheden en beperkingen van robotica leeromgevingen werd een experiment georganiseerd met 4 leerkrachten en 48 leerlingen uit groep 8, die samen 24 tweetallen vormden. De lokale instructie theorie impliceerde een leerkracht-onafhankelijk leerproces aan de hand van een instructieboekje en enkele leerkracht-gestuurde reflectieve besprekingen. De leerkracht-onafhankelijke cursus over robotica concepten was ontworpen op basis van (a) inzichten verworven in de eerste vier studies en (b) beginselen van geleide reconstructie.

Een onderwijs experiment werd uitgevoerd waarin de tweetallen een aantal taken uitvoerden die betrekking hadden op respectievelijk de concepten "functie", "systeem", "bediening" en "SRA". Nadat de reeks beschikbare taken rondom een bepaald concept waren uitgevoerd volgde een reflectieve bespreking tussen de leerlingen en de leerkracht. Voorafgaand aan de uitvoering van het onderwijs experiment zijn de leerkrachten individueel voorbereid op hun rol bij het uitvoeren een reflectieve discussies. Er bleek echter geen gelegenheid te zijn voor een uitgebreide en grondige opleiding zoals uitgevoerd in de studie van hoofdstuk 4. Vanwege praktische beperkingen hadden de leerkrachten weinig tijd beschikbaar. Het leerproces is onderzocht door het verzamelen en analyseren van gegevens uit de aantekeningen van de leerlingen, uit transcripties van video opnames van de discoursen en uit transcripties van de interviews met de leerkrachten en leerlingen. Er is bewijs dat veel leerlingen moeilijkheden hadden met het begrijpen van de niet-waarneembare interne processen van de concepten "functie", "systeem" en "besturing" en dat slechts een paar leerlingen het "SRA” concept begrepen. Het doel van het onderzoek was, beter te begrijpen hoe de interventie werkte en kon worden verbeterd. Het beoogde doel werd echter slechts ten dele bereikt waardoor de focus in het onderzoek verschoof naar de verwante vraag: waarom behalen leerlingen niet het beoogde inzicht niveau van robotica?

Daarvoor, werden de bevindingen geclusterd via condensatie van de ruwe gegevens en door het zoeken naar patronen en verklaringen via een twee-stappen methode gericht op het eerst verkrijgen van beschrijvende vermoedens en ten tweede op het formuleren van verklarende vermoedens.

Om te beschrijven wat leerlingen aankunnen zijn vermoedens over het leerkracht-onafhankelijke leerproces geformuleerd en getest tegen de dataset. Er werd vermoed dat leerlingen in staat waren generieke inzichten met betrekking tot concepten "functie", "systeem" en "besturing" te begrijpen en toe te passen. De leerlingen bleken echter minder succesvol wanneer de taken betrekking hadden op de abstractere interne analyses en processen. Vooral de beslisprocessen gebaseerd op logische, causale of voorwaardelijke redenaties bleken voor de meeste leerlingen te moeilijk.

Vermoedens over de gesprekken leidde tot de conclusie dat leerkrachten voornamelijk vraag-antwoord cycli gebruikten om de ervaringen van de leerlingen te bespreken en nauwelijks andere scaffolding technieken gebruikten om het inzicht bij leerlingen te verdiepen. Dit leidde tot overwegend oppervlakkige discoursen. Onderwerpen die moeilijk te begrijpen waren zoals interne processen en causale en conditionele redenaties werden nauwelijks diepgaand bediscussieerd.

Uit de bevindingen werd duidelijk dat het inzicht dat leerlingen in robotica processen hadden beperkt was tot lineaire en eenvoudige als-dan-redeneringen en dat leerkrachten een betere voorbereiding nodig hadden om een verdiepend reflectief discours te kunnen voeren. Het leek leerkrachten te ontbreken aan een attitude en perspectief dat nodig was om een reflectief discours te houden dat leerlingen kon helpen bij de ontwikkeling van een dieper begrip van de technologie. Het blijkt dat het de leerkrachten en leerlingen ontbreekt aan een echt technologisch perspectief. Ze interpreteerden en analyseerden de robot vanuit het perspectief van een leek gebruikmakend van een sociaal-cultureel referentiekader en focusserend op *wat* de robot moet doen en *waarom*, in plaats van *hoe* van de robot wordt verwacht dit te doen. In deze zin blijft de robot een black box.

In hoofdstuk 7 zijn de resultaten van de individuele empirische studies verzameld en geïnterpreteerd. Richtingen voor toekomstig onderzoek en praktische implicaties zijn verwoord.

Het voornaamste doel van dit proefschrift was het ontwikkelen van een dieper inzicht over hoe in verschillende didactische settingen kennis geconstrueerd kan worden gebruikmakend van robotica directe manipulatie omgevingen. De studies die in dit proefschrift zijn beschreven dragen bij aan theorievorming over het leren en onderwijzen met mind tools. Er werd aangetoond dat de toepassingen en didactische omgevingen bruikbaar waren voor het bevorderen van actief denken en een onderzoekend- en ontwerpgebaseerd probleem oplossend gedrag. De didactische ontwerpen resulteerden in actieve en constructivistische processen, waarin kennis werd gecreëerd, geherstructureerd en verankerd in betekenisvolle en authentieke contexten, en waren gebaseerd op persoonlijke en collectieve wederzijdse kennisuitwisseling door de lerenden zelf aangestuurd. In retrospectief blijken deze kenmerken in overeenstemming te zijn met de beginselen van krachtig leren zoals beschreven in hoofdstuk 7.

Het proefschrift heeft ook bijgedragen aan de theorie over leren en onderwijzen van robotica door te demonstreren welke concepten voor de meeste leerlingen haalbaar waren en in welke begripsmatige omvang. Deze bevindingen droegen bij aan een beter inzicht over wat leerlingen kunnen leren van een leerkracht- onafhankelijk leerproces. Ook werd duidelijk dat een deskundige leerkracht het conceptueel leren van leerlingen kan verbeteren door discussies over robotica te benaderen vanuit een technologisch perspectief in plaats vanuit een sociaal-cultureel perspectief van de leek. Niettemin blijven er vragen en onzekerheden met betrekking tot de grenzen van het begrip van leerlingen wat betreft het programmeren op basis van causaal en conditioneel redeneren.

De onderzoeken hebben ook bijgedragen aan de ontwikkeling van inzichten over vakdidactische kennis voor robotica onderwijs. Het werd duidelijk dat een goed ontworpen robotica professionaliseringstraject voor leerkrachten gericht moet zijn op het combineren van de conceptuele inhoudelijke kennis en praktische didactische vaardigheden die het leerkrachten mogelijk maken onderzoekend of ontwerpend leren van leerlingen te ondersteunen. Het zelf ervaren van een didactisch traject vergelijkbaar met de manier waarop van de leerkrachten werd verwacht dat ze onderwezen hielp om zelf de moeilijkheden van leerlingen te begrijpen en droeg bij aan een beter inzicht hoe deze moeilijkheden in een dialoog te overwinnen zijn.

In de onderzoeken van deze dissertatie is gevarieerd in de mate van ondersteuning van het leerproces van de leerlingen. De ondersteuning varieerde in een begeleiding door een expert leerkracht tot leerkracht onafhankelijk. Op eenzelfde manier is gevarieerd in intensiteit en uitgebreidheid van leerkracht professionalisering. Op basis hiervan kan gezegd worden dat succesvol onderwijs in de onderscheiden robotica concepten in principe mogelijk is wanneer leerlingen begeleid worden door een deskundige leerkracht. Tevens is het waarschijnlijk ook mogelijk leerkrachten zo te professionaliseren dat ze leerlingen ook zelf kunnen begeleiden. De huidige onderwijs condities zijn echter te beperkt om dit zonder meer in te voeren. Het laatste onderzoek echter biedt aangrijpingspunten om de daar gevolgde didactische aanpak verder en met meer succes uit te bouwen.

In de afsluiting wordt geconstateerd dat dit proefschrift heeft bijgedragen tot de ontwikkeling van kennis over de haalbaarheid van het onderwijzen en leren over robots in een ecologisch valide situatie, dat wil zeggen in een reguliere groep 8 basisschoolklas. In het Nederlands basisonderwijs is er een groeiende belangstelling voor het introduceren van robotica. Echter, de meeste Nederlandse basisschoolleerkrachten zijn niet vertrouwd met dit onderwerp. De resultaten, van het ecologisch valide onderzoek, suggereren dat lessenreeksen over het leren van robotica gebaseerd op een geleide reconstructie didactiek alleen productief kunnen zijn als de voorbereiding van de leerkracht en de inhoud van het instructieboek in overeenstemming zijn met een technologisch perspectief en concepten opneemt die gerelateerd zijn aan de interne werking van de robot en de complexe SRA-programmering.

Het vermogen om een “technologisch perspectief” te nemen werd geïdentificeerd als een belangrijke factor in het onderwijzen en leren over robotica. Het leek de belangrijkste oorzaak van de kennelijke afwezigheid van een technologische discours (misschien wel gekoppeld aan bepaalde manieren van kijken naar de wereld) en vooral van een "robotica discours", die leerkrachten en veel leerlingen ervan weerhield black-box aspecten te openen, zoals de interne werking en constructie van robots.

De studies in dit proefschrift waren exploratief van aard en hebben nieuwe richtingen voor onderzoek voortgebracht. Er werd geconcludeerd dat toekomstig onderzoek moet investeren in het bestuderen van: de gevoeligheid en attitudes van leerkrachten voor wetenschap en technologie, hun scaffolding vaardigheden in een context waarin leerlingen technologische problemen oplossen, de voorwaarden die nodig zijn om leerlingen te helpen op een zodanige wijze het SRA-concept te ontwikkelen dat ze in staat zijn hun inzichten toe te passen bij robotica problemen.

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Curriculum Vitea

Lou Slangen (1954) graduated from the Catholic Teacher Training Institute in Maastricht in 1976. After that he studied pedagogy at the University of Utrecht where he attained the master's degree in 1981. From 1981 to 1997 he worked as school counsellor and educational advisor in the field of educational innovation and school development at the Educational Counselling Office "Onderwijsbegeleidingsdienst Midden-Limburg". Simultaneously he followed an ICT training (AMBI) and obtained several modules. In his work for the Educational Counselling Office he acted as regional project leader for innovation projects which aimed at the implementation of ICT in Dutch primary schools. Since 1997 he works at the teacher training institute "Fontys Pabo Limburg", first as educator specialized in science, technology and ICT, and from 2008 onwards as associate lector Science and Technology Education at the teacher training institute "de Nieuwste Pabo". He was involved in several ICT and science and technology based innovation projects for teacher training institutes and primary education. From 2001 to 2010 he was project leader at the "Support Center Science and Technology Midden-Limburg". Here he was responsible for the regional elaboration of a national program that aimed at the implementation of science and technology in primary schools. From 2004 to 2006 he was part time posted to the national office "Platform Bèta Techniek" in the Hague where he worked as project leader science and technology for the Dutch Teacher Training Institutes. From 2004 to 2008 Lou Slangen further participated in the knowledge study group "Educational Functions of ICT" where he investigated ICT based mind tools and the idea for the PhD study emerged. In 2009 he won the first prize of the "Fontys Knowledge Contest". From 2014 until now Lou Slangen is part time posted to "LOBO" the national organisation of Dutch Teacher Training Institutes in order to conduct the national innovation program "Wetenschap en Technologie in de Pabo" (Science and Technology in the TTI).

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