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How design-based research and action research contribute to the development of a new design for learning

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In this article, we explore how Action Research and Design-Based Research can be combined and used in the development of educational robotic tools. Our case study is the development of an educational tool called Number Blocks, and it combines physical interaction, learning, and direct feedback. Number Blocks support a child's understanding of place value by allowing the child to experiment with large numbers. The tool was developed in collaboration with a class of 7- to 8-year-old children and their mathematics teacher. In this article, we compare and synthesize elements from different research methodologies and argue that these elements can constitute a structured approach to projects combining educational design research with new learning technologies. Key elements of the approach that has been developed include: acknowledging user input, active participation, developing a theoretical pre-analysis, and using an iterative approach.

INTRODUCTION

The purpose of this article is to describe how elements of two different methodologies can contribute to the design of interactive educational tools. The methodologies involved are Design-Based Research and Action Research. Action Research was originally developed for social sciences as an iterative and participatory methodology. This approach has, over time, been used to address design issues. Design-Based Research is a branch of educational research that uses the design of educational interventions to exemplify and develop theories of learning. The interrelation between these approaches is described and illustrated by the design of the Number Blocks system.

The Number Blocks tool is a modular robotic system based on a platform called I-BLOCKS (Nielsen, 2008a). The system can be used to support number learning in mathematics. More specifically, the educational goal is to support children's understanding of place value by physically allowing them to play with multi-digit numbers, which have complicated names in Danish (Ejersbo, 2009). The target group is children between the ages of 5 and 8. The development was carried out in an experimental design process that actively involved a class of normal schoolchildren and their mathematics teacher. This experiment was cross-disciplinary, combining the areas of robotics, informatics, and educational research. Number Blocks combine physical interaction, learning, and direct feedback.

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Wenger inspires our learning approach and directs our focus to the social environment and active participation in a community of practice (Wenger, 1998). In our case, the community is the classroom, the pupils and their teacher. Wenger describes participatory learning in this way:

Learning as participation is certainly caught in the middle. It takes place through our engagement in actions and interactions, but it embeds this engagement in culture and history. Through these local actions and interactions, learning reproduces and transforms the social structure in which it takes place (Wenger, 1998:13).

In the quotation above, Wenger emphasizes the learner's active participation as a key to learning. In the design process, our goal is to develop new and meaningful ways for the children to interact and participate with each other and the robotic tool. In the design process, we try to develop new modes of participation and thereby new ways of learning. Even though we take as our starting point the social theory of learning developed by Wenger, we acknowledge the value of working with local, domain-specific theories (diSessa and Cobb, 2004). In our case, we have augmented the overall social conceptualisation of learning with specific knowledge from mathematics education about how the Number Blocks system helps achieve the learning goal.

The question addressed in this article is: how can Action Research and Design-Based Research help the design of robotic educational tools and put a focus on active participation?

The structure of the paper is as follows:

1. We introduce the underlying technology and the results of the design process. We describe in summary how the educational tool "Number Blocks" works. There is also an introduction to the educational goals of the system and how children interact with the system. In a previous article, we focused on the learning process (Majgaard et al., 2011).
2. Afterwards, we describe the methodologies that have inspired us, Action Research and Design-Based Research; we describe how we use them in our experimental design process. The interplay between these research methodologies is our focus in this article.
3. Then, we introduce our experimental research process, which combined elements from Action Research and Design-Based Research and resulted in an iterative research design that acknowledges the children and teachers as co-designers while insisting on theoretically-related learning goals. We present a summary of each iteration of the experimental design process of the Number Blocks tool.
4. Then, we discuss how Action Research and Design-Based Research have influenced the design process and the research design. We discuss the research focus, research versus practice, empowerment, fixed versus

emerging goals, alignment with learning theory, and active participation. 5. Finally, we summarize and conclude.

NUMBER BLOCKS

The overall idea behind the development of Number Blocks is to use interactive hands-on building blocks, I-BLOCKS, as a development platform for designing new learning materials that support new modes of interaction and participation to help children make abstract concepts concrete in new ways. The Number Blocks tool helps children learn place value and the concept of numbers.

Cross country comparative investigations have shown linguistically-determined differences in the concept of numbers and in the understanding of place value (Ejersbo & Misfeldt, 2011; Dowker et al., 2008; Miura et al., 1989). These studies concludes that one of the reasons for these differences lies in the extent to which the words used to denote numbers reflect in a regular way the base ten place value system (Dowker et al., 2008).

Danish words for the numbers between 1 and 100 do not reflect the base ten place value system in two ways: (1) the words for digits greater than 10 (11, 12, 13...) and units of ten (20, 30, 40...) do not in any significant way relate to the names for the digits 1-10, and (2) the numbers are spoken in reverse order compared to how they are written as digits in the base ten system. As an example of these two problems, you would say 'fem-og-tres (five-and-threes)' to express the number 65. 'Tres' (60) is an inflection of 'tre' (3), showing how the Danish number words relate to the base 12 and 20 systems, which are no longer used (Ejersbo & Misfeldt, 2011; Ejersbo, 2009). The reversed order of digits between 20 and 100 also affects larger numbers such as 27,000 (in Danish, 'syv og tyve tusinde' – that is, 'seven and twenty thousand'). The algorithm for creating larger numbers in Danish is described in Figure 1a.

It is generally acknowledged that the learning of mathematics can be considered an embodied activity (Johnson, 1987, Nemirovsky et al., 2004). Furthermore, concept formation in mathematics is intimately related to the representations that are used when working with the specific concept (Duval, 2006; Steinbring, 2006). The Number Blocks tool provides an embodied interaction with two representations that are crucial in the formation of a number concept: namely, the number written as digits and the words used for a number. Number Blocks are an example of a digital manipulative because they enable interaction between abstract concepts (Zuckerman, 2005).

The Number Blocks tool is based on the I-BLOCKS platform. The I-BLOCKS platform is a user-configurable modular robotic platform developed and tested through several prototype and application generations (Nielsen, 2008b; Nielsen, 2008c).

The Number Blocks implementation and instantiation of the I-BLOCKS technology allows children to explore the concept of numbers and the place value system in a tactile way, focusing on the way large numbers are constructed from digits and on the spoken names for these numbers. To create Number Blocks, each I-BLOCK module had a single digit attached to each face of the block. The digit labels were registered with the built-in accelerometer, so that when a module determines which face is currently facing upwards, it also knows which digits are facing in every direction.

The user connects the Number Block modules in lines to create numbers, which is equivalent to writing digits in lines to create larger written numbers. The spoken numbers are consecutive playbacks of samples of recorded children's voices. A number algorithm plays the samples in the correct order. Figure 1a gives the correct spoken order for 16,458,432: by following the arrows from the left we get 16 -> 'millioner' -> 400 -> 'og' -> 8 -> 'og'->50->'tusinde', etc.

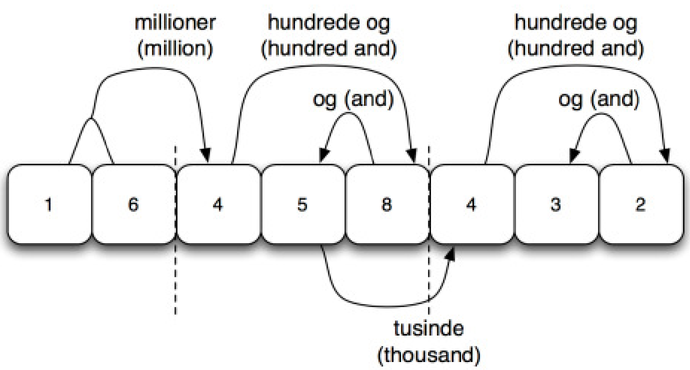

Figure 1a. The Danish system of pronouncing numbers.

Figure 1b-c. To the left: Pictures from our final session. The children enjoyed making large numbers. To the right: The handy size of the blocks supported collaboration and playful investigation.

The Number Blocks tool combines audio and physical interaction. When the children connected the blocks, the system expressed the combined digits as feedback, e.g. if "2" and "3" are connected the system will audio play "23" (if "2" is placed as the first digit). This gives the learners hands-on experience for learning place value. The interactive blocks gave the children new opportunities for active participation. We believe that active participation is closely related to successful learning processes, a position supported by Wenger, who also believes that new knowledge is developed through active participation in a social context (Wenger, 1998).

We found that Number Blocks contributed to the learning process in several ways (Majgaard et al., 2011): (1) The blocks combined mathematics and play; (2) they included and supported children at different academic levels; (3) the repeatability of the sound, made the sound act as a representation and the rhythm helped the children to pronounce large numbers; (4) the size of the blocks made it easy for the children to collaborate and for the teacher to intervene, and the modular block concept gave the children a new perspective on building and combining digits; (5) The children were playing, interacting, building, and learning about place value – all at the same time. This created a new context for learning mathematics.

USING METHODOLOGICAL ASPECTS FROM ACTION RESEARCH AND DESIGN-BASED RESEARCH

In this specific project, our methodological approach is an attempt to balance three different concerns: user participation, theoretically-underpinned research, and the development of new technology. In order to develop the Number Blocks tool, we worked on the assumption that active participation by teachers and pupils could: (1) improve the novelty of the solution developed, (2) distribute the ownership of the innovation, and (3) increase the usability and relevance of the solution.

Educational technology differs from "task-solving" technology by allowing (or even requiring) users to learn about a new topic. In the case of Number Blocks, the pupils could not be expected to describe or understand the inherent difficulty in the Danish words for numbers. This led us to supplement the 'user as co-developer' approach with a theoretical understanding of the learning envisioned and the problems we expected to encounter. These concerns led us to apply a methodological approach using Action Research and Design-Based Research. We combined Action Research and Design-Based Research in the hope of obtaining: (1) a participatory design methodology for educational tools; (2) iterative cycles of intervention and reflection; (3) a qualitative hermeneutic methodology; (4) support for permanent change in learning processes, and (5) the ability to build on and develop the theory of the number concept. These points are explained in more detail in the following.

Action research (AC)

Action Research is a collaborative inquiry process in which a change is introduced to an interactive field in order to uncover basic patterns and mechanisms in this field. These insights are used to make improvements. This method brings a change in the behavior of the target group into focus. It is used in various fields such as information systems (Baskerville, 1996), collaborative learning and technology (Riel, 2007), and the design of technology (Figueiredo, 2007).

Experiments and critical reflections are the core of Action Research, allowing learning from and through practice (Lewin, 1946). Action Research builds on experimental interventions and activities in which practice and science must go hand in hand (Nielsen, 2004). Kurt Lewin is considered to be the founder of Action Research (Nielsen, 2004). Lewin describes the Action Research process as being like a spiral staircase in which each cycle:

> *...proceeds in spiral of steps each of which is composed of a circle of planning, action, and fact-finding about the result of the action. (Lewin, 1946:38)*

The action is carefully planned before the event. The action is the physical intervention with the target group, which takes place in the target domain. Fact-finding takes places after the intervention and has four functions: (1) the action is evaluated; (2) the evaluation gives planners an opportunity to learn and gain new insights, (3) it provides the basis for correctly planning the next step; and (4) it constitutes a basis for modifying the overall general plan (Lewin, 1946).

This type of research is supposed to result in permanent changes in social structure. A change in social structure is compatible with a view of learning as situated in a social context. In this project, children and their teacher are participants in the design process and their approach to robot technology as a learning tool is supposed to change as a part of the design process.

Lewin describes Action Research as a kind of "social engineering" or "social management" that explores the conditions and effects of social action and research leading to social action.

> *It is a type of action-research, a comparative research on the conditions and effects of various forms of social action... Research that produces nothing but books will not suffice. (Lewin, 1946:35)*

Action Research has subsequently been described as a hermeneutic science (Nielsen, 2004) in which knowledge about the target group's social and cultural conditions is used as a starting point. Hermeneutics here means that the researcher has an initial understanding about the target group and the research field, and this is used in planning and conducting the intervention. Each intervention is evaluated, and this forms the basis for a new understanding. Figure 2 below is based on a hermeneutic perspective of Action Research.

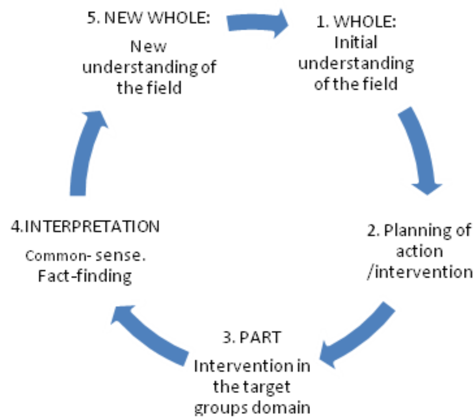

Figure 2. Action Research from a hermeneutic perspective

The hermeneutic circle in Figure 2 describes the interaction between part and whole. Each part can only be understood if the whole is involved and vice versa. It is this relation between part and whole that creates new understanding and enables an interpretation (Højbjerg, 2004). In Action Research, it is not only the researcher who gains new understanding but also the target group, which is empowered through transformative actions.

Action Research provides a new understanding of the subject field of research and, in this case, Action Research provides a new understanding of the learning processes with robotics as a fulcrum. The truth criteria and validation of Action Research are that users should experience the design process as successful and that they should be able to find elements of their own participation in the final design. Action Research is a method that focuses on social processes in which both the researcher and the researched are actively participating (Nielsen, 2004; Lewin, 1946). Action Research projects are often described in a sociocultural framework, since the focus on empowerment and social change fits well with an understanding of learning as situated in a social context. In our methodology, we have taken inspiration from Action Research and included children as active participants in the process of creating new technology. The resulting classroom values and the students' collective identification with the technology as something that they have been part of creating is most clearly captured through a sociocultural lens. Action Research collocates with a sociocultural view of learning. The target group's active participation is one of the points of Action Research. In this way, Action Research supports our search for new modes of participation in digitally-supported learning processes.

Design-Based Research (DBR)

In this study, we attempt to develop a new learning tool and generate knowledge about the conception of numbers. In that sense, our approach correlates to the growing number of researchers who describe their work as Design-Based Research. Design-Based Research is best understood as a response to educational research, based on the premise that laboratory studies of learning and quantitative surveys do not respect context and process sufficiently (Barab, 2006; Misfeldt, 2010; The Design-Based Research Collective, 2003). Design-Based Research works with a broad concept of design are iterative, respectful of context, and are theory-oriented.

What we mean by a broad concept of design is the development of "technological tools, curriculum, and especially theory that can be used to understand and support learning" (Barab & Squire, 2004). The iterative aspect of Design-Based Research is found in the repetition and regular modification of the intervention. This aspect is closely linked to respect for context – on one hand, respect for the particular in each context and, on the other hand, the desire to develop theories of a general nature. Barab (2006) writes that Design-Based Research uses small generalizations, that is, knowledge that is general enough actually to inform others (and with a certain depth) working in similar situations.

One typical model for Design-Based Research (Cobb, 2001) can be described as a design cycle (figure 3) that relates the two important aspects of Design-Based Research – the design and the empirical investigation of the design in use. The design intervention should always be considered together with a set of hopes, hypotheses, or other forms of theoretically-based ideas about how the intervention will work in a classroom situation. The other important aspect of the design cycle is empirical investigation in which the combination of the designed intervention and the envisioned learning trajectory are put to the test.

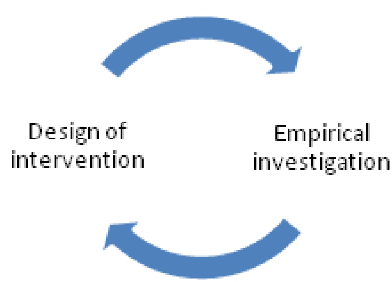

Figure 3. Design cycle

The argumentative grammar of Design-Based Research builds extensively on the relation between envisioned learning and empirical investigation (Cobb and Gravemeijer, 2008). In our project we have made an initial theoretical analysis of the influence of the base ten place value system and how it is adapted differently in written and spoken language (see sections 3 and 5.1).

The Design-Based Research literature gives rather specific guidelines as to what we should require from a theoretical framework – namely, the potential to address the issue at stake in a way that captures both the envisioned and the studied learning processes (diSessa, Cobb, 2004). There is a great need for theories that are very specifically related to the learning objective at stake, sometimes described as domain-specific theories. In our project, we have used state-of-the-art knowledge about the cognitive role of semiotic representation in mathematical activity to support our initial analysis of the difficulties with number names. This allows us to describe the cognitive conflicts that emerge from the two different systems for speaking and writing numbers.

OVERVIEW OF OUR RESEARCH PROCESS

Our experimental research involved a development process that was conducted in four phases (see figure 5).

Figure 4. (1) Pre-analysis and planning, (2) interaction-driven iterative design, (3) concluding interviews, (4) analysis of the empirical material obtained. All operations with the target group were recorded on video to facilitate subsequent retrospective analysis.

Phase 1: This phase resulted in a plan for the number of interventions, the selection of a target group, and the decision to work with the same group of children throughout the experiment. It was considered acceptable to work with the same group of children, since it was the qualitative nature of learning with Number Blocks, and not learning effectiveness, that was being investigated. During phase 1, we also did a pre-analysis of the technological platform and gained knowledge about place value and the target group. We also settled on design guidelines, and the idea of empowerment was acknowledged in the research group.

Phase 2: A number of iterative cycles were conducted. Each cycle consisted of an intervention in which the target group participated in the design process (see figure 2). The cycle consists of planning, intervention, evaluation, ideas, and implementation. The cycle was repeated 5 times in this project.

A summary of the cycles can be found in the next section. The elements in the iterative cycles are somewhat different from Figure 2, that shows Action Research from a hermeneutic perspective. This is because we have focused on new ideas and innovation instead of strict fact-finding. In later iterations, the focus changes back to fact-finding (see the summary of the design process).

Phase 3: In this phase, a final interview takes place. In our case, 8 of the children and their teachers were interviewed. They were asked questions related to the design process and the ostensible learning process.

Phase 4: This is the final phase in which the empirical data are analysed with respect to the research questions.

Initial theoretical analysis of difficulties with number names

As described in the introduction, the base ten place value system is a very important part of the number concept as it is taught in school. This is hard for young children to learn in their early schooling. Part of the reason for this is that there is no logical connection between the base ten system and the words we use in Danish for the numbers. Students are, therefore, put in a situation in which they are simultaneously learning a difficult but logical system of written numbers and a series of apparently more or less arbitrary names for these numbers. Therefore, we suggest that it makes sense to develop technology that combines a socially-situated and tactile experience of placing digits in a certain order and how this relates to what value the digit represents with the words we use for this number.

We envisioned this problem addressed through developing a set of interactive numbered blocks that can be assembled into all sorts of numbers: these blocks should somehow be able to say aloud the names of these numbers.

The development of mathematical concepts is related to the multitude of representations of these mathematical concepts (Steinbring, 2006; Duval, 2006; Ejersbo & Misfeldt, 2011). In order to understand the nature of the problem of learning number names, we applied a specific theory from mathematics education. The epistemological triangle connects concepts to the signs that represent them and to mathematical objects in a reference context (Steinbring, 2006). In some cases, there is an interchangeability between the reference context and the sign/symbol, because the same sign can serve as a reference context for a mathematical concept (left side of the triangle) in some cases and as a representation of a mathematical concept (right side of the triangle) in other cases (Steinbring, 2006). Taking the epistemological triangle as our point of departure, we can represent the situation as shown below:

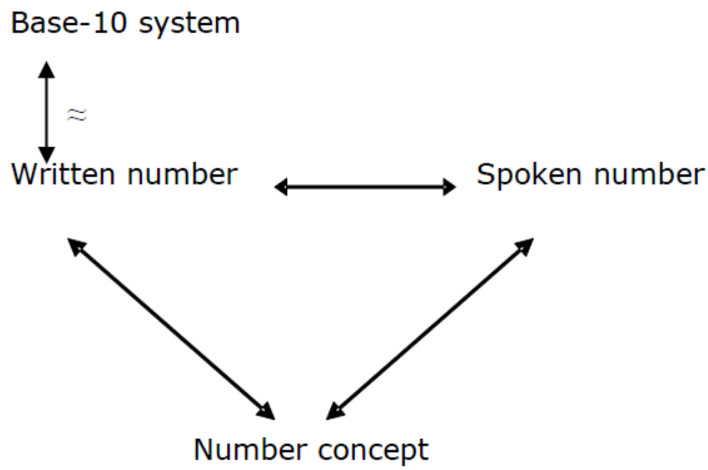

Figure 7: The influence of written and spoken numbers on the number concept. The written numbers reflect the base-10 system completely, from Ejersbo & Misfeldt (2011).

The epistemological triangle shows that the relation between the written number and the spoken number influences the number concepts that individuals develop. This is due to the mutually representational nature of how the written number signifies the spoken number and how the spoken number signifies the written number. The robotic system supports the combination of written and spoken numbers and, hence, addresses the issue of learning the names of numbers. Children playing with or learning from the Number Blocks will be challenged with respect to the relationship between the names of numbers and the written symbols. The interactive blocks could address these problems by allowing a playful interaction with numbers and their names. Our hope was that children's competence in remembering the names of two-digit numbers would increase if they were shown how the spatial placement of a digit influenced the quantity it signified. This theoretical pre-analysis was one voice in the design process that allowed us to focus our observations on the children's linguistic and representational behavior.

Apart from attempting to understand and untangle the cognitive aspects of the problem with the Danish number names, we also envisioned how the children's participation in the design process would affect the way we designed the tool, the user tests, and the didactics. We saw the children and their teacher as a community of practice and decided that our tests should take place in their normal classroom setting. Testing had to take place in small teams, and the teacher was supposed to play an active role. Moreover, active participation should be a dominant design guideline: this meant that the digital application should support and enhance active participation in the way the digital activities and the feedback were constructed. The activities were also supposed to support collaborative work.

Summary of the design process

Our iterative design process included five sessions with our target group, each lasting approximately two hours. The themes for the sessions were: (1) getting to know each other and the technology; (2) brainstorming and decision-making; (3) sound recording; (4) testing the prototype; and (5) testing the prototype as a didactic tool.

Intervention 1. Getting to know each other and the technology. The children tested out an existing I-BLOCKS music application (Nielsen et al. 2008b). The goal of the session was to evaluate the potential of I-BLOCKS with the target group and to get to know each other in order to make future cooperation easier for both children and researchers.

Intervention 2. Brainstorming and decision-making. The goal of this session was to generate good ideas for creating a suitable educational tool on the I-BLOCKS platform. The children had ideas about how to use the blocks for mathematics, e.g. that one could add and subtract using the blocks.
Aside from brainstorming with the children, we also had a session with a group of mathematics teachers from the same school. They suggested that the blocks could be used to help children by saying the numbers out loud. They told us that Montessori had some exercises with bricks and positional notation. In an earlier brainstorming session, the research group had had a similar idea. We decided to design a system that helped explain place value and to extend the system to include number operations at a later time.
Since active participation was a part of our sociocultural approach to learning, we wanted the children to become active participants while using the system. Feedback from the system was supposed to support active interaction and participation. The feedback was auditory and based on the dynamic physical structure of the I-BLOCKS, based on which side was facing upwards (see section 3).

Intervention 3. Sound recording and development of the first prototype. The next step was to record enough samples of voices saying the names of numbers to be able to synthesise pronunciation of the relevant numbers. To involve the children as co-designers in the design process, we chose to use the children's own voices. In this step the focus was on empowerment of the learner. By being allowed to contribute directly to the design process, the learners became engaged and felt that they contributed to the design. Several times in later interventions, the children pointed out who said what in the system.

Intervention 4. Testing the prototype. The goal of this session was to test usability and to assess whether there was enough potential in the design to proceed. Our initial observations suggested that the children were interested in creating large numbers (Figure 1b): they were clearly interested in using

Number Blocks to make as large a number as possible, either with all the cubes or with a specific selection.

Our initial concerns about the Danish number names were centered on the first 100 numbers, but the interventions showed that large numbers were very interesting for the children. This fact came as a surprise to the teacher, since the class was only working with two digit numbers at that stage.

Another observation was that the children were able to play with Number Blocks. The intervention showed that the children (in groups of four) were able to create small games and competitions with the blocks (see figure 1c) without being guided by the investigators. This was a surprise in the sense that this prototype version of Number Blocks was designed without intended gameplay. Furthermore, the observations suggested that collaboration and competition were aided by the fact that the blocks fit nicely in a child's hand.

Our observations suggest that the size of the blocks supported physical play, including group interaction (see figure 1c).

Intervention 5. Testing the prototype as a didactic tool. This session was primarily undertaken to confirm the findings of the previous interventions. We worked with groups of four children. In this intervention, the mathematics teacher participated in and organized the children's work with the blocks.

The purpose of including the teacher was to observe the didactic potential of the blocks and to hear the teacher's views on the potential uses of the blocks for learning. The teacher did see a number of potential uses and spontaneously developed didactic activities involving the blocks.

In one case, the teacher asked two groups of the children each to pick three Number Blocks. The groups then competed to construct the largest numbers. The children built the numbers 995 and 955, and then they pronounced the numbers. The first group needed their teacher's help, and he pointed at the specific block and helped with the pronunciation. The other group pronounced the number without hesitation. The children could easily point out the largest number. Then, they connected the numbers and the 'comparison cube', and the system repeated the pronunciation and comparison. The children listened and commented on the voices in the system. Afterwards, they did similar activities with larger numbers. See pictures of this specific case below:

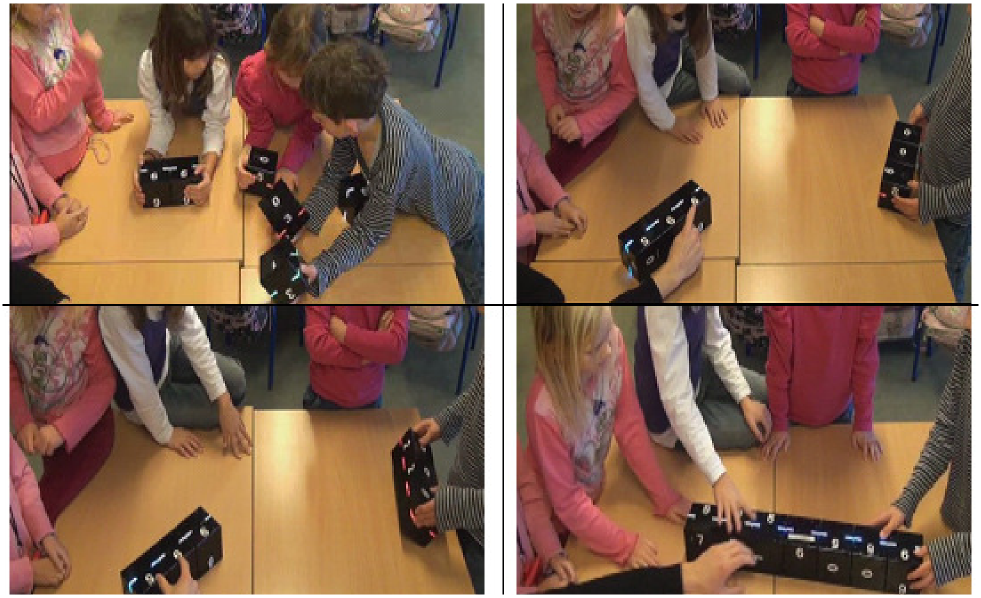

Table 1. Still images from the video of the last intervention

DISCUSSION OF DESIGN-BASED RESEARCH AND ACTION RESEARCH IN OUR PROJECT

In the design of Number Blocks, we found it constructive to select elements from different methodologies that could enrich our research focus. Since educational robotic systems are an emerging field, we decided to take an explorative and open research approach. This means that we did not want to fix learning goals entirely prior to our investigation. At the same time, we wanted to make a useful educational tool that addressed an interesting problem area. We wanted to explore the potential of learning through participation: this meant that the research method should encourage participation. Finally, we needed a methodology that respected the nature of our work in which design and intervention are linked and developed iteratively. This led to four methodological focus areas: (1) a research process model (for instance, iterative versus stage-gate model), (2) empowerment and participation, (3) emerging versus predetermined learning goals, and (4) alignment with a theoretical framework. This discussion is organised around these four themes.

Research process (see the table below). Design-Based Research has focused on learning and the development of better learning processes involving digital technology. Design-Based Research relates to theory and requires the formulation of an envisioned learning trajectory related to theory. Action Research has a more general focus on changes in social behavior and on empowering the group with which the researcher is working. Design-Based Research and Action Research share an iterative process model in which interventions and analysis follow each other. The main difference between the research processes suggested by the two approaches lies in the extent to which the pre-analysis must be formulated and related to theory. By combining Action Research and Design-Based Research, we ended up with the process model in Figure 6.

Empowerment and ownership (see the table below). Action Research focuses more explicitly on empowerment and ownership than Design-Based Research. In a sense, participative and empowered users are of key importance to the Action Research process. Empowerment means that the users are in control and, in this case, may affect the design process. The users' ownership of the project enhances the change that constitutes the goal of the Action Research process. In our case, the children's participation is a part of the design and learning strategy.

Active participation (see the table below). We wanted to explore new forms of participation and interaction between children and educational robotic systems by inviting the children in as active creators as well as users of a developed design. The children constructed numbers while they connected the cubes, and the cubes responded by pronouncing the numbers correctly. This is an example of active participation in relation to the use of Number Blocks. The target group also participated actively in the design process. For example, the children and teachers gave feedback on usability and participated in brainstorms on learning goals and game ideas. Furthermore, we recorded the children's own voices and used them in Number Blocks; the investigation supports that this acted as a symbol that enabled the children to have a sense of ownership in the project.

Fixed or emerging learning goals (see the table below). In Design-Based Research, the learning goals are fixed from the beginning (van den Akker, 2007), and there is a a pre-analysis relating these goals to theory. By contrast, Action Research works with much more fluid and emerging goals. In our case, we did not fix the learning goals entirely from the beginning, because we wanted to empower the target group, and we did not know the precise potential of the robotic system with this target group. In our case, we developed the idea of working with the place value system, in part, from an idea suggested by a group of mathematics teachers at the school. When we decided to work with the place value system and fit it into the design, we developed the idea further it partially from our pre-analysis based on knowledge from mathematics education and the theoretical framework that we had adopted. The pre-analysis involved a learning goal. This learning goal changed between interventions 4 and 5 from focusing on two digit numbers to focusing on creating and comparing larger numbers.

The envisioned learning trajectory and the claim of a strong pre-analysis, which is valued in a Design-Based Research approach, are very close to the hermeneutic idea of research that is crucial in Action Research: the major difference is the extent to which this pre-analysis relates to theory.

Alignment with theory of learning (see the table below). In Design-Based Research, the researcher needs to define or choose a learning perspective in the initial phase. And the researchers need to operationalize the learning perspective in design and evaluation guidelines. This method, in principle, supports many types of theories of learning, including our perspectives. Action Research has a focus on active participation, which is in line with our socio-cultural perspective. Moreover, the method supports the active participation of the children and their teacher in the design process, which aligns well with the constructionist view of the learner as an active creator of artifacts.

	Design-Based Research	**Action Research**
Research focus	Focus on learning, development of better learning processes that involve digital technology Learning trajectory Hermeneutic research method Iterative	More general: "change of social behavior" Hermeneutic research method Iterative
Research < -> practice	Focus on research allows a strong a priori analysis	Focus on practice
Empowerment and ownership	No focus	Empowerment, participative users, awareness, changing the target group Ownership
Active participation	No focus	Active user participation
Fixed versus emerging learning goals	Fixed learning goals Iterative	Emerging learning goals Iterative
Alignment with theory of learning	Aligns with different theories	Social theory of learning predominant. Number Blocks as a shared project for the class.

Table 2. Overview of the design and research focus

The table above provides an overview of the important design and research parameters. In our research, we had a special focus on research versus practice, empowerment of the user, fixed versus emerging learning goals, the method's alignment with theories of learning, and active participation.

SUMMARY AND CONCLUSIONS

The question explored in this paper is: how can Action Research and Design-Based Research enrich the design of robotic educational tools and place a focus on active participation?

We introduced the two research methods: Action Research and Design-Based Research. And we used ideas from both methods in the design of Number Blocks. This combined method gave us a design and research structure for our project. We also explored new methods of user participation in the design process. The children participated both as learners and as co-designers.

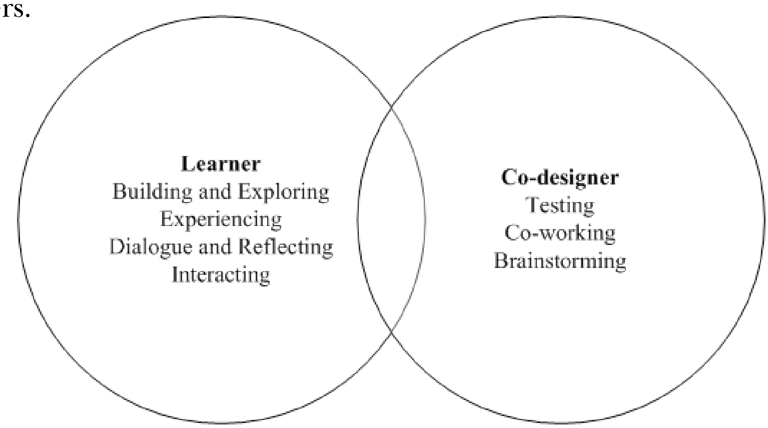

Figure 6. Overview of modes of participation

In brief, the children participated as learners and co-designers (see the figure above). When they participated as learners, they were actively using the newest version of Number Blocks. They were building numbers and exploring how their names were pronounced. During the learning process, they were in dialogue with other children and their teacher. The children discussed the pronunciations and reflected on pronunciation and how to subtract large numbers. When the children participated as co-designers, they had different roles: they were usability testers, they were co-workers when we recorded their voices, and they participated in the initial brainstorming.

Action Research and Design-Based Research enriched the design of Number Blocks in the following areas:

- Acknowledging the users' input and co-design abilities – showing, if possible the users' influence on the design in prototypes and product;
- Developing a strong pre-analysis related to the learning goal and relevant theoretical constructions;
- Using an iterative approach in which insights from early interventions were tested and developed in later interventions;
- Enabling learning goals to emerge gradually;
- Enabling users to participate actively in the design process;
- Learning during the design. The children learned to pronounce numbers during the design process.

Both methods endorse an iterative approach to design and change. In our work, we found value in combining the different methods because of our specific methodological requirements: the empowerment of the target group, active participation, rich pre-analysis, focused technological design, embodied interaction, and the possibility for emerging goals.

Design-Based Research contributed with its focus in educational research-For example, we did a pre-analysis of the place value system and the learning difficulties that were involved in the Danish language. Design-Based Research allowed us to envision how the results of the design process could support learning. The Design-Based Research method, however, had no focus on technological design and did not acknowledge the children's contribution to the design process. Hence, it alone would not have been an efficient methodological approach for empowering the children and their teachers. Action Research gave us the possibility of focusing on new modes of participation. For example, the children contributed to the brainstorming sessions, we used their voices in the system, and they came up with ideas to develop challenging number games. This method also involved the teacher in the didactic design.

Action Research also allowed for emerging goals. In our case, we did not know how the interaction between the target group and the robotic system would affect the level and direction of the learning goals. For example, to our surprise, the children were fascinated by large numbers, and this made it possible to set higher goals. There was also an unexpected synergy between the systems of rhythmic vocal pronunciation and the way the children participated. The children adapted to the systems of structured rhythmic pronunciation, and this helped them pronounce the numbers. Because of our research method, we were able to adapt our learning goal in accordance with how the children interacted with the prototype.

The researchers came from cross-professional backgrounds in robotics, informatics, and pedagogical research. The focus on research methods made us aware of how the different research areas contributed to the design and research process. The elements selected also suggest a promising methodical framework for future cross-professional educational design projects.

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