A Robotics-based Learning Environment Supporting Computational Thinking Skills – Design and Development

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***Abstract*— This Research to Practice Full Paper presents the development of a robotics-based learning environment using an educational design research approach. Contemporary teaching should prepare learners for everyday and working life, suggesting that this can only be achieved by implementing Digital Education from primary education onwards. Since computer science education is planned to be anchored in the Austrian primary school curriculum as an interdisciplinary competence development, research into teaching methods and content suitable for this area is becoming increasingly necessary. In this context, the transfer of innovations and didactic approaches into teaching is one of the biggest challenges. Introducing coding and robotics would be a possible strategy. Educational robotics provide access to real-world scenarios and offer age-appropriate possibilities to explore digital aspects of living and working environments. Combined with narrative methods, such as digital storytelling, problem-solving skills could be developed. Since the implementation of computer science in primary education requires practical and theoretical knowledge, an educational design approach is used that takes this aspect into account and allows close interaction between researchers and practitioners. This paper focuses on investigating a feasible and effective robotics-based learning environment for developing and supporting problem-solving skills at primary school using the learning and teaching method digital storytelling. Hence, the development of the learning environment and the didactic approach gained from qualitative results of interviews and observations from the first cycle of the research project are presented, providing plausible arguments for further implementing this robotics-based learning environment.**

Keywords— computational thinking, educational robotics, digital storytelling, primary school

I. Introduction

Computational thinking is now included in many primary school curricula worldwide [1]. The aim is to introduce computer science education, develop problem-solving skills, and generate interest in technological careers. Austria's primary school curricula are currently being reformed. As part of the reform, computer science education is to be anchored as a cross-curricular competence development [2] at primary level. In this context, the transfer of innovations and didactic approaches into the classroom is one of the biggest challenges. Educational robotics could be a possible method by focusing on hands-on activities and combining analog and digital concepts. Although there are already successful individual initiatives [3] in Austria in which educational robotics is used to introduce computational thinking, programmable robots in schools are still the exception rather than the rule. Therefore, a close theory-practice link in a playful way seems to be of considerable importance in computer science didactics, especially for young learners, to implement innovations sustainably [4]. The educational design research approach [5] is applied to explore this, enabling close interaction between researchers and practitioners. To reach many teachers and provide a viable concept for primary schools, researchers and practitioners have designed a learning environment that aims to implement computer science education and promote computational thinking skills using digital storytelling. The project aims to provide didactic approaches and materials for teachers. The research project's overarching research question is to investigate the characteristics of an interdisciplinary learning environment focusing on robotics and storytelling to support primary school students to promote their computational thinking skills.

This paper focuses on the first cycle of the development of the learning environment using educational design research. The goal of this work is to investigate the usability and practicability of the learning environment and to examine observed intended and unintended learning activities. The following paragraph provides an overview of the theoretical background. Then the methodology of educational design research is described, and the research design of our study is presented. After a short overview of the prototyping phase, the study of the first cycle is presented. The article finishes with a conclusion and an outlook on future work.

II. Background Work

A. *Computational thinking*

The term computational thinking (CT), first mentioned by [6] is mostly described as a problem-solving process [7], and there are several definitions and components of this process [7]. BBC Bitesize [8] formulates four main components that make up computational thinking: First, problems are broken down into smaller ones ("decomposition"), then consideration is given to whether a solution exists for a similar problem ("pattern recognition"). Then only the basic information remains ("abstraction"). Finally, a solution strategy can be designed ("algorithm"). International researchers use the term "computational thinking", which was mainly coined by Wings' article [9], in which she proposed "computational thinking" as a fundamental skill for everyone to integrate computer science in general education. Computational thinking is thus increasingly becoming a key competence for future scientific and technological progress and it is now more necessary than ever to familiarize learners with this competence [10]. For Humbert et al. [11], in addition to an adequate implementation of computer science as a creative design area for problem-solving, corresponding didactic concepts are also required. As digitization, scientific innovation, and technological advances continue to change the nature of problems and solve them, interest in promoting computational thinking among K-12 students has increased. It is now seen as an essential skill that every young learner should possess [12].

B. Problem-based learning

To foster computational thinking even at primary school level, problem-based learning is the most common learning approach [13], mainly when carried out with the support of technological tools for a successful learning process. Problem-based learning is an instructional method that uses real-life scenarios and topics familiar to students as a context to develop critical thinking and problem-solving skills [14]. Students are encouraged to collaborate and engage in problem-solving activities to gain problem-solving thinking skills and expertise in computer science education. Educational robotics allows teachers to create engaging lessons that foster interest in technology, student motivation, and computational thinking [15]. Problem-based learning activities enable students to design concepts and hypotheses to try out and solve with the robots during the intervention. Students actively influence the learning process as they develop their problem-solving skills [13].

C. Educational robotics

One opportunity to introduce students to computer science education and foster computational thinking skills at the same time is the use of educational robotics. Playful programming with programmable robots is seen as a promising way to promote problem-solving already in young learners [4] and could possibly lead to the development of interest in technical professions later on [15]. The haptic use of programmable floor robots, such as Bee-bots or Ozobots, makes them particularly suitable for younger children [16]. Esteve-Mon et al. [17] describe the robot as a tangible object to interact with the environment through programmed instructions. It can also serve as a tool for developing cognitive skills and fostering creativity [18].

D. The robot Ozobot

The robot used in this study is the Ozobot (Figure 1). An Ozobot is a little robot that moves on two wheels and uses color sensors to follow lines and recognize color codes. Working with the Ozobot offers opportunities to develop competencies while enjoying themselves, playing with the robot in computer science and technology, and promote teamwork, collaboration, and social competence. Due to the easy entry into programming the Ozobot, even younger children can work with the small robots. The simple handling of the Ozobot makes it possible to use this valuable tool and its diverse functionalities in various teaching units and achieve the learning objectives set [19]. Since these small robots can be used at different levels, they are suitable for simple programming and more complex tasks and programming solutions. Ozobots are well suited for interdisciplinary use [18] and storytelling activities [20].

Fig. 1. The robot Ozobot

E. Digital storytelling

Digital storytelling is a teaching and learning method that combines traditional storytelling with digital technologies[21]. The aim is to create digital stories based on a combination of different artifacts [22]. Kordaki et al. [23] analyzed the stages of digital storytelling. They proposed an initial framework that shows the relationship between the stages of digital storytelling and the development of computational thinking skills. "Digital storytelling can foster creativity" [24] as well as help to develop other 21st century skills such as collaboration, communication, and critical thinking as each group of students shares their knowledge with the others and reflects on the outcome [25]. Digital storytelling can be integrated into classroom practice in a variety of ways [21]. One promising approach is the use of educational robotics in combination with the method of digital storytelling. In their study, Leoste et al. [20] describe the great potential of educational robotics because it combines the advantages of gamification and storytelling. Storytelling activities with problem-based tasks create a connection between the real world and the classroom, making learning more fun and increasing students' motivation [26].

III. FRAMEWORK

A. Educational design research

Educational design research [5] provides the theoretical framework for this research. It serves to investigate the design, development systematically, and evaluation of educational interventions as possible solutions to complex problems in educational practice, aiming to increase knowledge about the characteristics of these interventions and the processes of their design and development [27]. What distinguishes educational design research from other forms of scientific research is its commitment to developing theoretical knowledge and practical solutions simultaneously in real-life situations. Many different solutions can be developed and studied through educational design research, including educational products, processes, or policies [5].

B. The research design of the study

Educational design research was chosen because the implementation of an innovation is to be investigated, and this is preferably examined to link theory and practice [28]. The research project aims to design a robotics-based learning environment that promotes computational thinking skills in primary schools and develops didactic approaches and design principles for pre-service teachers and in-service training. The design research approach is carried out in a cyclical process consisting of design, implementation, review, and redesign to capture aspects of the learning environment, setting, and learning activities.

The design of the study is based on a prototype cycle and two further cycles of field tests in which the learning environment is tested in different schools (Figure 2). Due to the Corona pandemic, this can only be done in selected schools and with fewer participants than planned. Finally, the research aims to establish design principles for the development of robotics-based learning environments. The overall design research aims to identify the characteristics of an interdisciplinary learning environment focusing on robotics and storytelling to support primary school students in promoting their computational thinking skills.

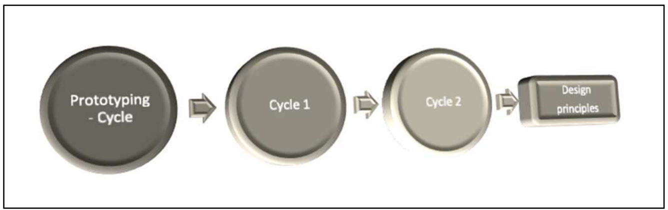

Fig. 2. Design of the research study

C. The prototyping cycle

The prototyping cycle included literature research, development of preliminary design principles [29] (Table 1), prototype development, and field testing. This cycle was evaluated in the alpha testing phase [5]. The field test took place in a primary school with 4th grade primary school students (n=19). After the evaluation, the intervention was further developed and improved. However, in the prototyping cycle, the first step was to evaluate whether the intervention fulfills the requirements and whether it is practicable and can be implemented effectively. The first findings of the evaluation and reflection show that both students and teachers appreciate the use of learning robots combined with storytelling. The teachers considered this approach a good possibility to implement computer science teaching in primary schools in an interdisciplinary approach while supporting computational thinking skills [30]. Furthermore, a case study in the prototyping cycle showed that it is possible to foster creativity with this playful approach [18]. Minor modifications were made regarding the teaching materials. In addition, the research team decided to include the method of digital storytelling to encourage further aspects of computational thinking even better.

TABLE 1. PRELIMINARY DESIGN PRINCIPLES

Preliminary design principles of the robotics-based learning environment
Choose an interdisciplinary approach
Provide tasks that encourage problem-solving thinking
Use age-appropriate robots and teaching material
Provide a learning environment to create solutions and own ideas
Enable communication and collaboration
Encourage a playful approach

D. The first cycle – beta testing

Since the prototyping cycle has already been conducted, this study focused on implementing and evaluating the first cycle. This cycle is mainly concerned with the tryout of the prototype learning environment in the school. Tryouts are used to investigate how interventions work, what participants think or feel about them, and what results they deliver. The evaluation of this cycle is called beta testing [5], which aims to identify opportunities for further development and optimize the learning environment. Beta testing is considered an essential phase of the study to develop the learning environment further. After the last tryout, another reflection phase takes place, which evaluates the learning environment and the students' learning processes in addition to the evaluation of the observations and a theory-based analysis based on them. The development of the learning environment and the study of the first cycle are described in the following chapters.

IV. DEVELOPMENT OF THE LEARNING ENVIRONMENT

The robotics-based learning environment developed and investigated in this research project is part of the "Fairy Tale Computer Science" project. The design of the intervention, which is the core element of the design-based research, aims to use programmable robots in an interdisciplinary approach in primary education. Furthermore, the problem-based approach [4] is used by giving the students an inquiry-based task.

Since the focus was on promoting problem-solving skills and creative learning, a theme was deliberately chosen that was familiar to most children. The choice fell on the topic of "fairy tales". The project "Fairy Tale Computer Science" sees itself as a work in progress and is intended to contain a collection of ideas that will enable teachers to establish a connection between digital media and the promotion of literacy in the context of fairy tales. To provide an interdisciplinary introduction to computer science education, the playful programming of robots is combined with the method of storytelling. The development of the project is based on the concept of the project "Computer Science - A Child's Play" [31] and on the four basic principles of creative learning, also known as the 4Ps (projects, peers, passion, play) [32], as they play a central role in the introduction to computational thinking.

The intervention consists of two units (Table 2), an introduction to Ozobot programming and a lesson with the fairy tale Little Red Riding Hood. The first unit starts with a description of the Ozobot and how it works. To foster collaboration and communication, the students are divided into groups. After that, the first programming experiences are carried out with paper and pens. Using the Ozobot basic card, the learners become familiar with the first programming codes. In the second unit, the fairy tale plot is repeated to ensure that the students are familiar with the topic. Then the students get their problem-based task in which they have to depict the fairy tale plot graphically. Students are asked to draw lines for the Ozobot and the details of the story. Then the students' task is to program the Ozobot so that it could follow Little Red Riding Hood's path through the forest, past the wolf, to her grandmother (Table 2/Artifacts). Several programming codes, such as turn right, speed up, etc. should be integrated. If there is time available, the students can also create appropriate costumes for the characters. Finally, the students decode the story because they retell the fairy tale using the lines and the codes. After that, they can give feedback to the others and how they liked the lesson.

TABLE 2. LESSON PLAN

Units	Unit 1	Unit 2
Title	***Introduction – Ozobots***	***Fairy tale - Little Red Ring Hood***
Learning goals	• Getting to know the Ozobot robot • Getting to know how it works • Getting to know the programming	• Telling the fairy tale Little Red Riding Hood • Knowing the plot of the fairy tale • Graphically representing the plot • Programming the Ozobot according to the plot • Retelling the fairy tale using the programmed lines and codes
Activities	• Experimenting • Drawing lines • Using the programming codes	• Telling the fairy tale or solving a riddle • Drawing the path of Little Red Riding Hood • Using appropriate codes, such as turn right, slow down, or speed up, etc. • Retelling the fairy tale • Filming the story
Artifacts		

V. THE STUDY

The study of the first cycle was conducted in three classes with primary school students (n=43) aged 8- 10 years in two different primary schools (Table 3). In each of the three classes, the introductory unit and the fairy tale unit were held consecutively on the same day. In one class, the time resources were limited to 60 minutes. The research questions that emerged from the literature review for the beta testing are the following:

- How relevant and usable do practitioners perceive and experience the intervention? (RQ1)
- What intended and unintended learning activities could be observed? (RQ2)

The methods for the evaluation were the following: observation, interviews, video recording, group discussion, and analyzing the created artifacts. The resulting documentation (criterion-based observation notes, video) serves as a basis for the subsequent analyses and reflections. A total of 19 teachers were involved in the reflection, divided into teachers (n=12) who conducted participant observation and teachers (n=7) who were shown the recorded lesson as part of an in-service teacher training, which was held online.

TABLE 3. PARTICIPANTS AND EVALUATION METHODS

Grade	Students	Time/ min	Evaluation	Teachers
3	total (n = 17); male (n=11) female (n=6)	100	observation, student feedback, interview, created artifacts	3 teachers (participant observation)
4	total (n = 14); male (n=8) female (n=6)	100	observation, group discussion, created artifacts	6 teachers (participant observation)
4	total (n = 12); male (n=5) female (n=7)	60	observation, video recording, created artifacts	3 teachers (participant observation) 7 teachers (non-participant observation)

VI. FINDINGS

A. *Relevance and practicability (RQ1)*

The question of how relevant and practicable practitioners perceive the intervention was clarified with the help of participant and non-participant observation using the recorded video and a short online survey during an in-service teacher training, which was held online. This situation provided the opportunity to analyze and discuss the evaluation right away. The in-service teacher training participants (n=7) have evaluated the learning environment by doing an online survey (Table 4) and a group discussion. The participants rated the criteria (4=strongly agree, 1=strongly disagree).

TABLE 4. RATING THE PROJECT

	N	Mean	Std. Deviation
Structure of the project	7	3,86	,378
Relevance/curriculum	7	3,86	,378
Practicability	7	4,00	,000
Achieving the learning goals	7	4,00	,000
Material resources available	7	3,29	,951
Calculated time	7	3,00	1,155
Valid N (listwise)	7		

The teachers observed agreed that the learning environment is very well structured (M=3.86/SD=0.378), highly relevant (M=3.86/SD=0.378), and very practicable (M=4.00/SD=0.000) and thus, students can achieve the expected learning objectives (M=4.00/SD=0.000). They also liked the teaching material and the robot (M=3.29/SD=0.951). One teacher mentioned that Ozobots would be ideal for this application but might be too expensive to acquire. However, there is skepticism about the estimated time (M=3.00/SD=1.155).

The same tendency was shown in the answers of the observing teachers (n=12) in the reflection phase immediately after the lessons at school. The teachers were also convinced that this unit can be integrated very well into the lessons and is promising. The teachers were enthusiastic about the playful introduction to programming and that the children enjoyed the storytelling. They also noted that it was interesting to see how the students approached solving the problem. Some groups discussed it first. Others started drawing the path of the Ozobot right away, trying out the codes repeatedly. Some of them only commented that the robots might be too expensive and would only be profitable if used more often. Another suggestion was to share the robots with other schools to lower the costs for each school. Concerning the calculated time, it was also considered that more time could be planned for the second unit and that this could be extended with creative making activities.

B. *Intended and not intended activities (RQ2)*

The observation results and the video recording analysis gave indications about the intended and unintended learning activities. The primary goal of these learning units is to promote narrative activities on the one hand and expand digital education in problem-solving and programming on the other. In this context, the use of programmable robots shows itself to be a particularly good example for promoting computational thinking. Through these concepts of problem-solving [7] are emphasized, which can also be found above all in the digikomp4 model [33]. In this interdisciplinary project, the problem is first formulated and then subsequently abstracted by visualizing the story's plot. Further steps of the problem-solving process [8] could be observed as the students formulate and discuss the problem-solving steps with each other. The analysis follows this. The structuring of the story, which becomes necessary through the drawing design and the planning of the programming, leads to a clear concept for retelling the fairy tale. In the fairytale retelling using the Ozobot, the story is then decoded again.

However, there are also numerous learning activities and competencies that were not the primary goal at all. By programming the robots while graphically creating the story, systems of order are built, and spatial skills are fostered. To reach a common goal by developing a problem-solving strategy, communication skills and the competence to collaborate are enormously promoted because the details of the story and its implementation are discussed, and an internal agreement is made within the group where responsibilities are defined and accepted. One aspect that could be observed, especially in the programming of the Ozobots, is the training of fine motor skills through the precise drawing of the lines and the precise sticking of the adhesive dots.

In addition, two other competencies gained should be mentioned. Firstly, these were social competence, the ability to work in groups, divide, assign, and fulfill different roles. The second was technological competence, using learning robots and digital media to record the story.

VII. DISCUSSION

The design-based research approach provided a viable research framework for the development and evaluation of a robotics-based learning environment. Relevant literature and concepts from the field of computational thinking [7] could be taken into account. In this design cycle of beta testing [5], the designed learning environment could be evaluated for relevance and practicability in a field test. The results show that teachers are convinced of the project's structure and relevance and consider it practicable. Only the time frame should be extended. The explorative approach of educational design research [28] also made it possible to investigate aspects that were not planned, and the course concept could thus be continuously improved. The observations and evaluations show that the narrative method [25] is a promising approach to provide an interdisciplinary and engaging and enjoyable introduction [20] to computer science education. It also became apparent in this cycle that the setting's structured approach makes texts more understandable to students through coding and decoding. This method could also be used to introduce children to literature creatively and to make word problems in mathematics more understandable. This research indicates the development of various 21st skills such as communication, collaboration, and creativity [10]. Furthermore, it is possible to promote additional competencies with a clear focus on narrative competence and computational thinking.

VIII. CONCLUSION AND FUTURE WORK

The simple introduction to programming the Ozobots makes it easy for primary school students to work with the little robots and gain their first insights into problem-solving skills and an approach to simple computer science concepts. Their appearance and ability to follow lines are fascinating and motivating for the pupils. This fascination with robots can help arouse interest in programming and computer science as early as primary school. It can contribute to awakening an interest in programming and computer science already at the primary level. Due to its diverse application possibilities at different levels and the combination of problem-based tasks from everyday life and the children's environment, the Ozobot can be well integrated across subjects. The observing teachers were particularly enthusiastic about how easily and playfully the digital storytelling method can be combined with the programming of the little robots. Nevertheless, many benefits arise from it, such as the promotion of social and methodological skills. Thus, the presented cross-curricular robot-based approach is a good example for implementing computer science in primary school and the simultaneous development of computational thinking skills.

After implementing this cycle, the learning unit will now be extended and implemented in a further field test at other schools. In addition, the combination of storytelling and programmable robots is also planned to be carried out with Bee-bots. A teacher training has already been conducted, and the collected experiences implementing this intervention will be published anytime soon.

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