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Pupil-robot interaction in a math card game: an iterative process of studying the use of social robotics in primary school math education

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Abstract. This paper explores the potential use of a social robot as tutor and playing partner in a primary school mathematics classroom. Our approach is using a math card game, based on the understanding of fractions, to study the pupil-robot interaction. We follow an iterative process consisting of three consecutive phases: (1) data collection involving a human playing partner, (2) a remotely controlled social robot as tutor and playing partner, and (3) a fully autonomous robotic tutor and playing partner. We present data collected from the phase 1 and 2 trials involving a total of 13 pupils (ages 10–12). The lessons learned from the first two phases are presented, as well as how these lessons can help inform future steps towards meeting the challenges presented by an autonomous robotic playing partner (phase 3).

Keywords: Social robotics, child-robot interaction, primary education, mathematics, math card game, wizard of oz

1 Introduction

Even though in its infancy, social robotics is a promising tool in education with various areas of potential applications [1]. Social robots may be an attractive addition in the classroom because of their exact retention of the learning interactions, their inexhaustible patience and their novel nature, (hopefully) resulting in higher pupil engagement. Although much research has been focused on the use of social robots in language learning and special needs education in primary school, little research has been conducted on the potential use of social robots in math education [2]. An exception to this is studies examining how social robots can provide feedback, which has received some attention [3][4][5]. One reason for the research gap is the wide range in complexity among typical mathematical learning tasks encountered in the classroom; while certain tasks are very structured and thus more easily automated, like drilling and learning the multiplication table, other tasks are much less structured, making it hard to predict the scaffolding needed by individual pupils. To strike a balance between the trivial and the impossible, we have examined the potential use of a social robot to support the understanding and use of fractions among primary school pupils. The choice of fractions as our focus is motivated by the fact that a successful understanding of fractions has been identified as a key (mathematical) developmental step, without which pupils will later struggle with learning algebra and beyond [6]; and improving children's competence with fractions is likely to facilitate overall gains in mathematics achievement [7].

To provide a familiar and bounded environment in which to study the pupil-robot interaction, the mathematical task has been put into the form of a domino-like card game played by the pupils and with the robot acting as a helpful playmate. We chose a domino-like game since they are quite common in Finnish schools, making it familiar to most pupils. Our research design uses a Wizard of Oz (WoZ) method, where one incrementally moves toward making the robot assist the pupils autonomously. The purpose of this paper is not to present an autonomous application, but to illustrate how this kind of process can be done and to share the lessons learned so far.

2 Theoretical background

As the ambitious end goal is to have a social robot that can behave autonomously and adequately, we need to start with a task that is simple and has clear, well-defined boundaries. To this end, as noted by Xin and Sharlin, games provide many opportunities for studying human-robot interaction [8]. Games are also clearly constrained, often social and, if correctly designed, also engaging. To take full advantage of the physical presence of a social robot, a physical game where materials can be physically manipulated is to be preferred over a digitally implemented one. This choice is also supported by research showing that humans, as embodied creatures, prefer to feel and touch real objects as opposed to manipulate virtual ones [9].

In exploring the pupil-robot interaction, within the context of a physical math card game, we are inspired by a WoZ methodology developed by Sequeira et al. [10]. There are two parts to their methodology; the first one is designing a robot program through iterative stages, the second is restricting the information the robot has in a given task before it is programmed to be autonomous, which makes the transition easier.

We will use a similar methodology to design a robot tutor and playing partner through three phases: (1) pupils will first play the game with a real teacher, (2) pupils will then play with a robot that is remotely controlled and, (3) pupils will lastly play with a robot that is autonomous. At each phase, the game interaction will be recorded and analysed to inform the design and implementation of subsequent phases.

3 Study overview and data collection

A total of 13 pupils (ages 10–12) attending grades 5 and 6 from a Swedish-speaking primary school in Finland participated in the research. All pupils attended voluntarily and had a written consent from their guardians allowing them to participate in the studies. Data was collected using the following methods:

- **Phase 1:** A teacher played the math card game with the pupils. The session was video recorded from multiple camera angles, and the teacher also documented, in writing, her thoughts after the game.

- **Phase 2:** A remotely controlled robot played the math card game with the pupils. The session was also here video recorded from multiple camera angles, and a teacher interviewed the students after the game. These interviews were all audio recorded.

3.1 The math card game

The card game consisted of 17 cards (Fig. 1). The aim was to correctly pair the yellow side of one card (the fractional representation of a number) with the blue side of another card (the decimal representation of a number). For example, the yellow side of the card with 7/8 can be correctly paired with the blue side of the card with 0.875. To make the cards easier to reference, they were all labeled with fruit or vegetable names in Swedish. The game was played by the pupils, with a tutor (a teacher or robot) providing instructions, support and scaffolding. It was the pupil that selected and placed the cards, and the tutor confirmed whether it was the right card or not. The tutor also provided help when it was needed. The tutor initiated the game by instructing the pupil to place the card labeled "Ananas" (0.875 | 1/2) on the board. After this, all cards were chosen and placed by the pupil. When all cards were paired correctly, they formed a circle of 12 cards, which signaled that the game was over. Five extra cards, that were missing a pair, were also included. Starting from the top-most card, the level of difficulty of the game increased slightly in the clockwise direction.

Fig. 1. When finished the playing cards formed a circle. The leftover cards which did not have a correct pair were placed in the middle.

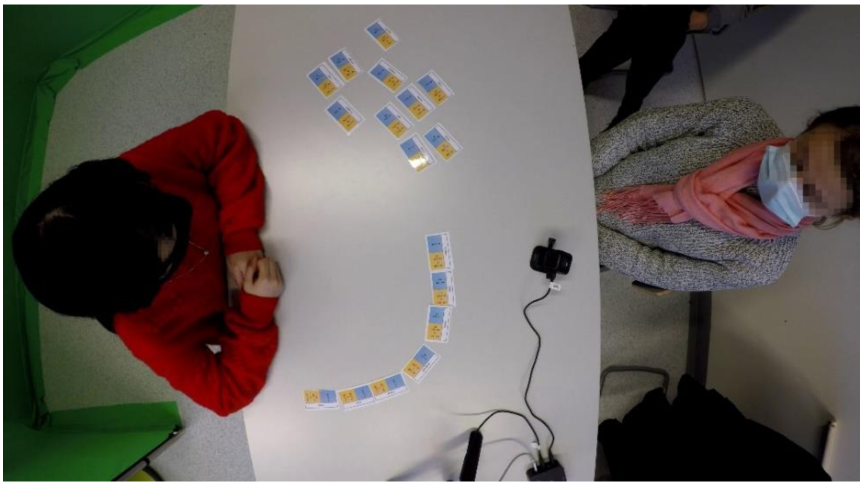

Fig. 2. Pupil playing with a teacher in phase 1.

4 Procedures and results

This section describes the two WoZ-phases and the results of the analysed data from the pupil-teacher and pupil-robot game interaction. At each phase, the results are presented as lessons learned.

4.1 Phase 1 procedure

The math card game was brought to the primary school, alongside with cameras for recording the interaction. Each session started with the teacher explaining the rules of the card game. Then, the session continued with the pupil playing the card game and the teacher helping, giving only limited support and scaffolding when needed (Fig. 2). An example of this was to ask if the pupil wanted to keep going or if they needed a hint. By restricting the amount of help in this way, the design was kept in line with methodology of Sequeira et al. [10]. Each playing session lasted 10-14 minutes and were 10 in total. After all the sessions were completed, the video recordings and the teacher's written reflections were analysed according to qualitative content analysis [11]. Two of the researchers coded the material and grouped it into identified categories. These categories were then discussed and iterated between all authors. The final categories will now be presented as lessons learned.

4.2 Lessons learned from phase 1

Lesson 1: Identifying right level of difficulty. To encourage learning, a task should not be too easy nor too hard [12]. The math card game was often challenging at some point. The pupils seemed to especially have problems when the denominator was not ten or something easily converted to it, for example five. Having easier cards in the beginning of the game, however, seemed to strike an appropriate balance in the level of difficulty.

Lesson 2: The problem of guessing. A natural consequence of the calculations sometimes being challenging is that the pupils often tried to guess the correct card, instead of trying to reason and calculate. It is, however, also possible that they often chose to guess because there were only a limited number of cards and therefore guessing was seen as a viable option. From a problem-solving point of view, guessing is certainly a valid strategy. However, for a guess to be pedagogically meaningful it should be followed by some reasoning or "proof" that validates the quality of the guess; this is not the case in the math card game, which makes it undesirable. This kind of guessing strategy is not unique to our study but seems to be prevalent in situations where you can proceed by guessing the answer, for example in digital tutoring systems [13].

Lesson 3: Adaptive scaffolding. Instead of blindly guessing when unsure, it is pedagogically more productive for the pupils to utilize scaffolding. Fortunately, the pupils seemed to respond well to this kind of support. A typical situation was the following:

> Teacher: You were pretty good at finding those which had 10 in the denominator. Can you change this one so it has 10 in the denominator as well?
> Pupil: Yes... or... I don't know how to do it — I've forgotten how to.
> Teacher: How should we proceed in that case.... But, how you do it is — at the moment, we have fifths, and five means that we divide it into five parts, or two such parts. If we had 10, we would need to divide it into 10 parts. And how many parts do we in that case have in total if these 10 should correspond to as much as 2/5?
> Pupil: I'm thinking of 0.4
> Teacher: 0.4 is 4/10, right?
> Pupil: Mm.
> Teacher: Is 4/10 the same as 2/5?
> Pupil: No, or wait a second...
> Teacher: Can you shorten 4/10 to 2/5?
> Pupil: Yes!
> Teacher: Yes.

In this case, comparing the fractions with tenths in combination with extending and shortening the fraction provided successful scaffolding. In other cases, imagining slices of a pie or a number axis were a successful strategy through which the pupil understood how to perform the calculation needed. What became clear from our analysis is that there are many ways of providing successful scaffolding. An experienced teacher often intuitively knows which strategy is likely to be the most suitable in a given situation. This expert knowledge is very hard to formalize and thus also a challenge to automate.

4.3 Phase 2 procedure

After identifying and discussing the lessons learned from our phase 1 trials, we started planning phase 2, that is, having the pupils play with a remotely controlled robot. Although intentionally constrained, the interaction in phase 1 was to a large degree free. As this was not possible with a robot, the interaction needed to be further constrained to realistically implement it, even in a remotely controlled scenario. To constrain the interaction, we decided to implement clear-cut turn-taking where the pupils first pick a card, ask if it is the correct one and then the robot confirms the answer as either correct or incorrect. We also decided to use a game board with empty slots on which the pupils could place each card to avoid confusion as to where to place a selected card.

The robot chosen for the phase 2 trials was NAO, developed by SoftBank Robotics. NAO's humanoid look, many pre-built capabilities and flexible API made this a suitable choice. NAO has also been used in numerous other studies. We created a graphical user interface implemented in JavaScript and Electron which communicated with NAO’s API. The program consisted of pre-defined actions, for example cheering the pupil on, but also had the option of using text-to-speech on the fly for cases where improvised speech was needed.

Since one of the lessons learned from phase 1 was the central role of scaffolding, we knew we had to implement part of this ability in phase 2 as well. The main challenge, however, was that whereas the scaffolding provided by a teacher could be very adaptive, this flexibility was not possible with a robot. We therefore decided to implement a rigid type of scripted scaffolding, providing two hints with every card: one generic and one which limited the number of possible answers. An example of the generic type was “The card says 2/5. How can this be stated in decimal form?” An example of the limiting type was “Is it card A or card B?” We also knew, based on previous experiences, that the pupils probably would want a human to turn to if the situation approached a breakdown [14]. For this reason, and to avoid having a pupil feeling uncomfortable being alone with the robot in the room, we opted to have one of the researchers present as well. However, this person would only assist when absolutely necessary.

In our phase 2 trials we had 6 pupils who had played the game before. The pupils were informed beforehand that they would now be playing the same card game as before, but now with a robot that was remotely controlled by us. The game interaction took place in a room where only one of the researchers, the pupil and the robot were present (Fig. 3). The robot stood on the floor and had the math card game placed in front of it and was controlled by another researcher who could follow how the situation unfolded via a live video feed from nearby room. The interaction started with the robot asking the pupil for their name, and then answering “Hi (pupil’s name)”; this acted as an initial icebreaker, often making the pupil visibly relaxed. After that, the robot explained the rules of the game, asked if the pupil understood them, and then the game started. With each card the robot asked the pupil to state what card they had chosen, after which the robot either said it was the right or wrong card. If the pupil provided too many wrong answers, the robot provided either of the two types of scaffolding. At the end of the game, when the cards formed a complete circle, the robot thanked the pupil and said goodbye. Immediately following the game, the pupils were interviewed about their experiences. The interviews were performed by one of their teachers who had accompanied them to the study. The video and interview data were analysed according to the same procedure outlined in phase 1.

Fig. 3. Pupil playing with the remotely controlled robot (NAO) in phase 2.

4.4 Lessons learned from phase 2

Lesson 1: Scaffolding is challenging with a robot. As mentioned, we were aware of how vital scaffolding was and that we needed to constrain the situation enough to implement it successfully with a robot. However, our generic scaffolding strategy was not very effective in supporting the pupil. Limiting the number of possible answers did not work either. What ended up happening was that some of the pupils relied only on the alternatives given by the robot. In other words, they took advantage of the rigid scaffolding as the game proceeded.

Lesson 2: The robot provides immersion and novelty. Multiple studies have show-cased pupils' fascination with robots [15], even though it less known how long this novelty lasts [16]. We could also notice this kind of fascination among some of the pupils; it was also clear through the interviews, where some of them described the robot as an intentional agent, something which has been noticed in other studies [17]. One pupil for example said:

> Pupil: [...] and it was a little bit weird that you didn't speak to a human, but to a robot — and not with a telephone or something like this, like an object you can lift or something like that — but that it still isn't a human and that it responds.

Others, however, did not lose track of the fact that it was a human controlling the robot:

> Teacher: Alright, alright. Did NAO seem smart?

Pupil: Well, not the robot itself. He was, like, controlled, but... I don't really know what to say [laugh].

Lesson 3: Variation and improvisation makes the robot more impressive. The times the pupils seemed most immersed and impressed was when the robot said or did things outside its predictable repertoire. Pupils were, for example, not amazed about the robot being able to check for right answers. However, they were impressed when it apologized for giving the wrong answer:

Robot: It was my fault
Pupil: [slightly surprised]
Robot: You were right in choosing "Rödbeta" (one of the cards).
Researcher: So you guessed right, "Rödbeta".
Pupil: Did I say that earlier?
Researcher: Yes, you did say it. NAO —
Robot: Sorry.
Pupil: Yes [smiles].

Lesson 4: Overestimating the robot's abilities**.** The fascination some of the pupils experienced might be why some overestimated the robot's capabilities [18]. One pupil, for example, commented that:

> Well, of course, if he was completely autonomous, he would in one way have the whole internet inside his head, so he would like know everything in that case.

Whereas another pupil said:

> I thought it would use its hands to play the game as well, to place — but it didn't...

This kind of physical functionality is, in reality, hard to implement.

Lesson 5: Turning imperfections into jokes**.** But even if the interaction often was immersive, it sometimes led to breakdowns [14]. What we noticed, however, was that joking about the ways the interaction failed helped to mitigate the breakdowns. For example, the robot did not always pronounce the Swedish words very well, but we made light of this by telling the pupils that the robot recently came from France (where the software is produced) and therefore did not know Swedish too well yet. This helped to make a problem into something fun instead and helped the pupils in accepting the robot's imperfections.

Lesson 6: Feeling uncomfortable with the robot. When things, however, did get too difficult, or the interaction in general felt unnatural and humor could not mitigate the situation, the pupils were quick turn to the researcher present in the room. This highlights the need for people to trust and feel at ease with the robot, a topic that has and continues to receive a lot of attention [19]. This is further strengthened by one pupil being nervous, and another even a little bit scared:

> Teacher: How did it feel to talk with the robot?
> Pupil: It felt weird, because I don't talk with robots, and but... It was a little bit scary when you looked at it in the eyes.

This highlights the importance of taking into consideration how different pupils might react to a robot.

5 Discussion

Our three-phase approach allowed us to gain insight into the different aspects of playing a math card game with a human compared to a robot (albeit remote-controlled). And even though the two WoZ-phases are different, there were nevertheless some recurring themes found in both. Especially salient was the strategy of answering by guessing, which due to the very restricted decision space needs to be discouraged so as not to provide a shortcut leading to less effective learning. It seems likely that the pupils in many cases opted for this strategy because it notably presented itself during the game; but it is also possible some of them opted to guess since they perceived that asking for help would diminish their sense of self-efficacy [20]. If this is the case, it could possibly be counteracted by making sure to provide more secure environment to those who need it and thereby helping them succeed. Even if this lack of self-efficacy is not the main problem, a secure environment is a good addition to a learning context. What also became apparent in both phases was the need for scaffolding, something that was clearly not adequate in phase 2 with the robot.

There were also clear differences between phase 1 and 2, a big one being immersion and novelty. It makes sense that the pupils saw the experience with the robot as more interesting since it was new for them. As mentioned before, however, it is not clear how long this novelty lasts. What might additionally decrease this novelty effect is that pupils sooner or later would realize that the robot is not as impressive as their idealized version of it; it cannot, for example, answer every question or do impressive and adaptive maneuvers, which the pupils in this case seemed to expect. This might explain their apparent fascination when it acted outside its script. Lastly, the latter phase was naturally more prone to breakdowns, which is not surprising; interaction with a robot is a complex task, after all. What often seemed to mitigate this, however, was a sense of humor. But the breakdowns could not always be prevented, which was apparent when some pupils seemed to feel uncomfortable playing the game with the robot compared to playing it with a teacher. This makes sense, however, since a lot of miniscule signals and aspects used in human communication and bonding are not available to robots [21]. There is also the aforementioned ambivalence of the robot as an intentional agent which could add to the uncomfortability.

6 Conclusions and future directions

Since we are approaching phase 3, making the robot behave autonomously, it makes sense to point out some interesting directions based on the lessons learned from phase 1 and 2.

A promising area is to provide adaptive scaffolding, something we clearly noted the need for. There are studies which have developed adaptive tutoring systems in social robots [3] [4] [5], but not in the context of a physical and interactive math card game. Something that could interact positively with both affective and subject scaffolding is having the robot provide a sense of security for the pupils who need it. This could lessen the problem of some pupils feeling uncomfortable around the robot compared to a human. Research into robots sensitive to social ques is nothing new [21], but it would be interesting to combine this with adaptive subject scaffolding. A potential and fruitful path to realize both affective and subject scaffolding is by increasing the level of personalization, which would further strengthen the already present interactivity. This aligns with the lessons learned from phase 2: the need for improvisation, variation, comfortability and humor.

We have presented our three-step plan which currently is in phase 2. Our goal has been to describe a possible, and hitherto successful, strategy to implement social robots into math education. In addition, we have wanted to share the lessons learned during the process. We also suggest some possible future directions based on the needs identified during the two first phases. Social robotics and pupil-robot interaction are still in their infancy, and we hope for more studies mapping the lessons and needs found in the field, enabling us to move forward.

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