RoboMath: Designing a Learning Companion Robot to Support Children’s Numerical Skills

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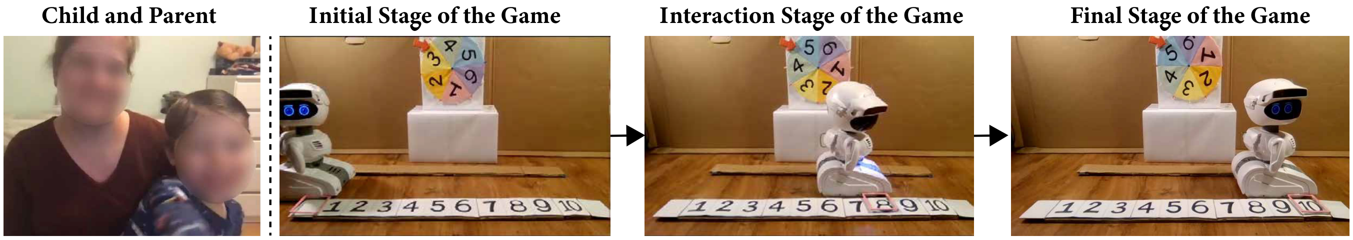

Child and Parent **Initial Stage of the Game** **Interaction Stage of the Game** **Final Stage of the Game**

Example
Audio-Visual-Social Condition:

(1) *Robot makes eye-contact with the child and asks for help going home*
(2) *Child says ``magic spinner spin!” to request energy for the robot*

(3) *Child tells the robot which number to go to based on the available energy*
(4) *Robot counts out loud as it moves on the number line*

(5) *Child repeats the interaction until the robot reaches home*

Figure 1: We designed a robot mediated linear number board game and explored young children’s experiences under three conditions: (1) visual-only, (2) audio-visual, and (3) audio-visual-social robot interaction. An example audio-visual-social condition in this figure demonstrates a child instructing the robot to move to a target number based on the spinner, as the robot moves it provides verbal and non-verbal social cues such as counting the numbers out loud, gaze contact, gestures, etc.

ABSTRACT

Children’s early numerical knowledge establishes a foundation for later development of mathematics achievement and playing linear number board games is effective in improving basic numerical abilities. Besides the visuo-spatial cues provided by traditional number board games, learning companion robots can integrate multi-sensory information and offer social cues that can support children’s learning experiences. We explored how young children experience *sensory feedback* (audio and visual) and *social expressions* from a robot when playing a linear number board game, “RoboMath.” We present the interaction design of the game and our investigation of children’s (n = 19, aged 4) and parents’ experiences under three conditions: (1) visual-only, (2) audio-visual, and (3) audio-visual-social robot interaction. We report our qualitative analysis, including the themes observed from interviews with families on their perceptions of the game and the interaction with the robot, their child’s experiences, and their design recommendations.

CCS CONCEPTS

- **Applied computing → Interactive learning environments**;
- **Human-centered computing → Empirical studies in HCI**.

KEYWORDS

Child-robot Interaction; Math Learning; Multisensory Feedback

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1 INTRODUCTION

At an early age, children begin to develop basic numerical knowledge, which underlies later development of mathematical skills

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and can predict their mathematics achievement [13, 20, 25]. Basic numerical knowledge—including counting, numeral identification, number line estimation, and magnitude comparison—is based on how children mentally represent numbers [5, 38]. However, failure to understand basic concepts of numbers may contribute to difficulties as young children advance in mathematics [15]. Incorporating games in mathematics education can help young children develop numerical concepts, as they offer a fun and engaging environment for young learners [31].

In particular, engaging in linear number board games strengthens basic number skills [44] and supports the goal of mentally constructing a linear representation of numbers [39], since it provides visuo-spatial and temporal cues [34, 40]. Children can see numbers linearly arranged on the board, and as numbers increase, they get farther from the starting point and they spend more time processing them. In addition to visual and spatial cues, information from other sensory modalities can be integrated into educational activities and further engage children and improve their learning experience [36]. In educational training, providing *multisensory* stimuli that integrates visual and audio cues, as opposed to unisensory stimuli involving visual or audio cues, helps learners perform more accurately [8, 19] and quickly [29] and enhances learners' memory [16].

As learning companions, social robots display a wide range of *social cues* for interaction [43], including body gestures, emotion expression, speech, and other bodily movements, that can serve as an additional channel of sensory cues and thus offer a unique opportunity to provide multisensory feedback during learning. Prior research suggests that integrating robots into children's learning process supports the development of academic abilities [1, 10, 22, 42, 45] and social skills [35]. While social cues of a learning companion robot can serve as an additional channel of sensory feedback and improve learning, they can also be a distraction from the activity and hinder learning [22, 47]. Overall, we posit that it is important to understand the ways in which a social learning companion robot might facilitate young children's math learning using linear number board games, and how different types of feedback (i.e., visual, audio, social) might affect learners' interaction and experience with the robot.

This work aims to close this knowledge gap by addressing the following research question: *How does the design of a learning companion robot that provides sensory and social feedback affect children's learning experience of numerical knowledge via a linear number board game?* We designed and compared three different robot conditions: (1) *visual*: a non-expressive robot that provided unisensory visual feedback by moving on the number line, (2) *audio + visual*: a non-expressive robot that provided multisensory feedback by moving on the number line and by providing verbal feedback, and (3) *audio + visual + social*: an expressive social robot that provided multisensory feedback by adding social behaviors, such as making eye-contact, moving its arms, and changing the colors of its lights, to the behavior it displayed in the *audio + visual* condition. To address our research question, we conducted a five-day study with children aged 4, consisting of four 20-to-30-minute game interventions over the first four days. We measured children's math skills pre- and post- intervention and conducted interviews with their parents. Here, we focus on our interview data with families, and are not reporting quantitative comparisons among the conditions (see §5.2 for more explanation). Our qualitative results suggest that families thought that the game and the robot were enjoyable and helpful in supporting numerical development. Parents provided several design suggestions, including design of visual feedback, supportive interaction strategies from the robot, incentives, and variations of the game. Overall, our findings offer design recommendations for robot-mediated learning activities in math for children.

2 RELATED WORKS

Previous studies indicated that children's early numerical competencies significantly predict later mathematics abilities [13, 20, 25]. Mental representation of numerical magnitude not only correlates but is causally related to arithmetic learning [5], and increasing linearity in number-line estimation independently explains improvements in estimation accuracy, which predicts mathematics achievements [38]. Siegler and Booth [38] suggested a developmental sequence of how children represent numbers. They rely on logarithmic representation in kindergarten and gradually shift to a linear representation as they age or gain relevant numerical experiences such as playing linear number board games. A logarithmic representation means that the perceived distances between adjacent numbers on the number line decreases as numerical magnitude increases [11], while a linear representation means that perceived distance between adjacent numbers remains constant as magnitude increases [6].

Playing linear number board games is suggested to be effective in improving children's numerical knowledge and linear representation of numbers [14, 33, 34, 40, 44]. Whyte and Bull [44] compared the effect of three board game interventions—linear number, linear color, and nonlinear number (e.g., number cards)—on children's basic numerical skills. The linear number board game presented numbers on a row of evenly spaced squares, while the linear color game presented only colors in the same arrangement. Children spun a spinner and moved their token the appropriate number of spaces. The nonlinear card game presented a number of objects on cards and children were asked to pick the card that showed the larger quantity. The most effective intervention was the linear number board game, which not only improved children's numerical knowledge but also fostered a shift from a logarithmic to a linear representation of numerical magnitudes. On the other hand, playing nonlinear *card games* only improved partial numerical knowledge but not numerical estimation accuracy and linearity [14, 44]. Other studies also demonstrated that playing a *circular number board game*, where numbers were ordered consecutively on a circular board, does not promote numerical understanding as effectively as a linear number board game [14, 39]. Thus, visuo-spatial cues of number arrangements are critical to the effectiveness of playing number board games on children's learning outcomes.

Combined with visuo-spatial cues, other sensory cues may contribute to children's learning, as multisensory information, in contrast to a unisensory one, better approximates natural environments and thus facilitates learning [2, 36]. The semantically congruent multisensory experience can enhance memory, which implies that multisensory stimuli receive better encoding in our perceptual system compared to unisensory stimuli [16]. Prior work shows that, for children at early ages, instruction with multisensory approaches is more effective than unisensory methods for language acquisition [3], incidental learning [8], reading [21], and number tasks [19]. The advent of educational technology provides opportunities for children to learn in multi-media environments involving multisensory information. Technology-mediated multisensory instruction enriches learners' experiences to be more "real life," facilitating their engagement and motivation to learn [2, 30, 41, 46].

Social robots are finding widespread use in educational settings as they afford human-like and embodied features, and encourage interactive learning [43]. Robots have been shown to help children develop various academic skills including language [1, 10], reading [27], mathematics [42, 43], and science [45] and may be more effective in educational contexts than other types of media (e.g., virtual agents) [12, 17], since they provide social presence and socially-enriched support [24]. Specifically related to our work, a study called MobiAxis suggested that social robots can be beneficial in teaching the notion of number line and multiplication in mathematics due to its embodiment, physical presence, and social aspects [42]. Brown and Howard [9] pointed out that while different forms of social interaction with robots promote children's performance, integrating verbal cues contributes to moderately better outcomes. Overall, we argue that classical board games, such as "Chutes and Ladders," that have inspired linear number board games might be particularly suitable for a learning companion robot, as players move characters on a path based on numbers from a spinner.

Although the use of robots in various educational settings has been examined, how robots can be involved in a number board game and how different types of sensory feedback influence children's learning experiences remain unknown. To understand how social robot interactions and different types of feedback affect children's experiences in a linear number board game, we studied children's and parents' experiences with a robot-integrated game that included three types of feedback from the robot: (1) visual-only, (2) audio-visual, and (3) audio-visual with social cues.

3 METHOD

3.1 Participants

Nineteen 4-year-old children (M = 54 months, SD = 3.6 months; 8 female, 11 male) participated in the study. We chose the age range of 4 as it is when children started to learn Arabic system and has the most potential to suggest the learning effect of the current intervention. C8 and C9 are twins, and they attended the study in consecutive but separate sessions. All participants were recruited from organizational mailing lists, including university faculty and staff. Recruitment information and pre-screening surveys were distributed to the parents/guardians of each child. The main inclusion criterion for the study was children aged 4-years-old at the time of signing up. We targeted children from English speaking families, in order to avoid language-related barriers.

3.2 Procedure

The study consisting of a pre-test, four same game sessions, a post-test, and an interview session with the family, was conducted over five days, with approximately 20 to 30 minutes each day. All sessions were conducted remotely via the video conferencing software Zoom[1]. Three user accounts were present in the video-call, (1) the child and parent, (2) the experimenter, (3) the linear number board game and the robot (See Figure 2). The linear number board game and the robot were physically located at the same room with the experimenter, who turned off the video throughout the game sessions, allowing child and parent to interact with the robot via the video-call. Throughout the sessions, the experimenter controlled the robot in a Wizard-of-Oz fashion (See Section 3.5) behind the scene.

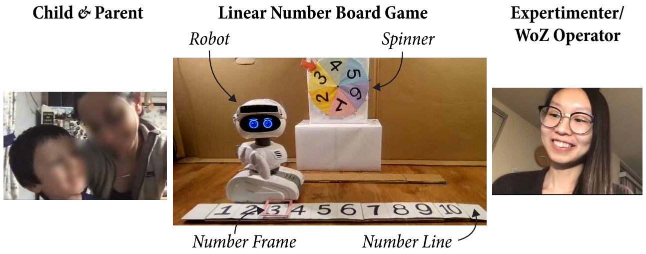

Figure 2: Parents and children (left) interacted with the following: a *robot* that had a *number frame* attached to it's body, a *number line* board game, and a *spinner* including the numbers from 1–6 (middle). The experimenter (right) facilitated the study and operated the robot in a Wizard-of-Oz fashion.

On the first day, we explained the study to the parent and the child and obtained informed consent. After receiving parental consents and verbal assent from the child, we started video recording the session. We asked the parent to fill out a demographic survey and assessed the child's math abilities as a pre-test. Then, the experimenter introduced the robot to the child by describing the background story of the robot, stating that the robot got lost and needed the child's help to move forward by spinning the spinner and telling which number the robot could go to. The experimenter guided the child to play the game with the robot by providing example interactions. The child played as many times as they wanted during the 30-min game session, and they were allowed to take breaks or end the game session anytime they preferred to. On the second, third, and fourth day, the child continued to play the same game based on their assigned condition with the robot repeatedly. On the last day, we assessed the child's math abilities as a post-test, and asked the child to select one out of five facial expressions to indicate their feelings towards the robot. We then interviewed the parents about their thoughts with open-ended questions, where they were asked to describe their observations on the child over days regarding the child's performance, feelings, and strategies used in the game. Parents were also asked about their own experiences and opinions including any design suggestions.

3.3 Game Design

The design of "RobotMath" was inspired by developmental psychology studies showing that linear number board games help

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[1] Due to COVID-19 precautions

strengthen children's number line mental representation and improve their numerical skills [39, 44]. Our notion of a linear number board game builds on classical board games, such as "Chutes and Ladders," and "Candyland" where the player traverses a path towards a goal based on the amount displayed on a spinner. Additionally, we follow established practice in the numerical cognition literature that identifies these interventions as "number board games" [39, 44].

Children played the game with the robot through a video-call, as the robot was located with the experimenter. The number board was about 96 centimeters long, including 12 horizontally arranged squares of equal size. The first and the last squares were blank to indicate start and end points, while the ten squares between them were labeled sequentially from "1" to "10," from left to right. During the game, children gave a voice command to spin the spinner to determine how many steps the robot could move forward on the board, and the robot moved to note the child's progress. The circular spinner was split into six different portions by colors and were labeled consecutively from "1" to "6" clockwise. The robot was equipped with a rectangular frame attached to its side that indicated where on the number line the robot was at, without blocking the number. All game design materials, including the robot, the number frame attached to the robot, the spinner, and the number board were carefully placed to ensure full visibility in the video-call account for the linear number board game (see Figure 2) allowing the child to easily interact with the robot over the video call.

At the beginning of the first session, the experimenter shared the story-line saying that the robot wanted to go home but did not have enough energy and spinning the magic spinner would create energy for the robot to move forward. The robot started on a blank space, on the left of number "1," and the goal was to help the robot reach home, located at number "10" (see Figure 1). The child would need to say "Magic spinner, spin", which indicated the experimenter to spin the spinner behind the scene. The end number on the spinner was the amount of steps the robot could move forward. To make the robot move, the child would need to add the number on the spinner and the robot's current location then tell which number the robot should go to. For example, if the robot was currently on number "2," and the child spun number "3," the child would need to add the two numbers and say "Go to 5" to make the robot move to number "5." If the number that the robot should move to went beyond 10, the child needed to say "Go over 10." The robot then moved past ten and expressed that it got home and felt grateful for the child's help. The robot then returned to 1 if the child expressed that he or she wanted to play a new round.

3.4 Robot Interaction Design & Conditions

We used the Misty II[2] robot and randomly assigned children to one of three conditions which had six, seven and six children in the visual-only, audio-visual, and audio-visual-social condition respectively. The robot visually demonstrated counting by moving step-by-step to the target number on the board.

Uni-sensory: Visual-only condition. This robot was similar to a movable game token. The robot always looked forward (towards the end of the number line) and moved when the child said the correct number. The child did not receive any verbal or social feedback from the robot. The experimenter or the parent provided prompts, instructions, or feedback for the child when needed.

Multi-Sensory: Audio-visual condition. In this condition, the robot only looked forward (toward the end of the number line) and gave *verbal prompts and feedback* to the child. It verbally asked the child for help to *get home* by saying "I want to go home but I don't have energy. Can you help me", then asked the child to spin the spinner by saying "You can say 'Magic spinner, spin"'. To start the game the robot asked "Could you give me some energy" and later asked "Could you tell me which number I can go to?" The robot also counted out-loud as it moved on the board. For example, if the robot was on number "2," the child spun a "3" and correctly said "go to 5," the robot moved and counted "3, 4, 5," and the frame attached to the robot highlighted the corresponding numbers. The robot also gave verbal feedback to the child. Following the child's first incorrect answer, the robot asked the child "are you sure that is the number? Look again!" After the second incorrect answer, it offered hints such as "maybe larger/smaller?" Following the third incorrect answer, it said "I think I know the correct number. I will show you" and demonstrated the solution by verbalizing the number it was on, the number spun, counting by moving step-by-step, and reaching the resulting number. These verbal responses were standardized, not personalized, for all children. Overall, the child not only visually saw the numbers as the robot moved but also heard the numerals, resulting in an *audio-visually integrated experience.*

Multi-Sensory: Audio-visual-social condition. Similar to the audio-visual condition, the robot provided *verbal feedback*, but instead of looking forward all the time, the robot reacted *socially* by making eye-contact, changing its head/arm movement, and LED light colors during the interaction. The robot made eye-contact via the camera over Zoom when addressing the child and looked at the map when moving or counting. It also moved its arms slightly up while moving and placed it down when stopped at a target number. Finally, it expressed basic emotions with facial expressions and changes in colored LED lights. All the verbal feedback for the child's correctness were identical with the audio-visual condition. Overall, the child had an *audio-visual experience with socially interactive cues* in this condition.

Wizard of Oz (WoZ) setup. The robot interaction was designed as a Wizard of Oz (WoZ) style and was operated by the experimenter. All verbal and social expressiveness of the robot were pre-recorded and the experimenter followed an interaction script listing when to initiate certain interaction components. Depending on the child's assigned condition, the experimenter used an interface to move the robot, set the interaction, disable/enable the types of sensory feedback (speech, emotion expressions, head movements, gaze, body gestures, and LED lights), or play the pre-recorded speech. For the *uni-sensory condition*, the experimenter only accessed the motor functions to move the robot. For the *multi-sensory conditions*, the experimenter initiated the speech for greeting, explaining the

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[2] https://www.mistyrobotics.com/products/misty-ii/

story-line, demonstrating the task, prompting the child to spin the spinner, and provide scaffolding for the child's incorrect answers.

3.5 Analysis

We conducted a thematic analysis [7] based on the post-study family interview transcripts to identify the themes related to parents' perceptions towards the game, the robot, and their child's experiences. The first two authors conducted the qualitative analysis after reviewing, reiterating, and agreeing on the coded transcriptions. The transcriptions were generated automatically using Zoom cloud services and reviewed for correctness by a study team member. When reporting our findings, we used the following notation: When quoting the parent from the fifth family we referred to them as P5 and when reporting a finding from the child from the ninth family we referred to them as C9.

4 RESULTS

We identified four themes from the interviews with children and parents. First, we discussed family's overall perception towards the game and how it changed over time. Second, families thought the robot was overall helpful and their perceptions on the robot in different conditions imply the strength and weakness of different types of feedback from the robot. Third, parents thought their children experienced challenges during the study due to insufficient prior knowledge or feeling of pressure, and observed strategies their children used. Parents also expressed how they supported their children during the game by providing clarifications, reminders, and helped them to point and count. Fourth, parents shared design suggestions for the interaction such as design of interactive visual feedback, design of robot's supportive methods, incentive design, and variation of the game.

4.1 Family Perceptions towards the Game

Across all robot conditions, parents and children had positive feelings towards the game, but their perceptions changed over time based on children's capabilities. In addition, the repetitiveness of the game introduced boredom but also confidence and helpful practices. Specifically, for conditions with verbal feedback (i.e., audio-visual and audio-visual-social condition), parents thought that the game was more interactive and that it supported children's independence.

For all robot conditions, both parents and children shared *positive feedback regarding their feelings towards the game.* Parents expressed that they felt the game was exciting (P1, P2, P4, P19), motivating and enjoyable (P2, P15, P19), fun (P2, P10), worth looking forward to (P16), less school-like (P15), and intuitive (P4) for their children. P1 described that "She [C1] was very excited having her next session." P15 stated that "He [C15] seemed to enjoy it. He would ask about it each day and I think he looked forward to it." P4 indicated that "She [C4] would always ask if she gets to play with Misty after school." In addition, some children expressed that they liked the game in general (C11, C14, C15, C18) or a specific component of it such as the robot or the magic spinner (C2, C11, C16).

However, C10 described her mixed feeling saying that she "like to do these activities because they're fun" but one part of her didn't like it "when it is hard." During the game, parents observed that children may feel more comfortable (P1, P12), confident (P7, P16), bored (P2, P6, P15), or frustrated (P2, P3, P4, P19) over time *depending on their capabilities.* Some parents (P1, P2, P3, P4, P16, P19) stated that their child usually got *frustrated* when they encountered difficulties in the game (e.g., fail to recognize a number). P3 said that "When he would get frustrated, he would want to stop." However, even though some children struggled in the beginning, some of them were able to figure it out over the days and *feel more confident* (P1, P3, P7, P12, P16). P1 mentioned that "on the second day, I thought she will give up. The third day she made it through feeling comfortable" and P16 said "she was pretty much confident the second day and the third day." Some children got *bored* over time during the game (P2, P6, P15), either because they were already good at the numbers from 1 to 10 or because they had short attention span.

Families perceptions of game modifications. For children those who already understand 1 to 10, we suggested them to try to count up over 10 and reach to higher numbers. As a modification of the game, the robot would physically restart from number 1 on the board when the child counted to number 11, 21, 31, etc. Some parents expressed that their child was excited about this modification and became more *engaged* (C6, C14, C15), while others said their child was *reluctant* to go over 10 and expressed they would rather keep repeating the original 1-to-10 version (C10, C11). P6 said that "at first he [C6] was very interested, but then it was a little too repetitive and easy so he was bored quickly" but "your modified version seemed to engage him," while P11 described "if she would have been a little bit more brave, like 11 through 19, but I guess no reason to push it." For those who have short attention span, we allowed them to take more breaks or shorten the length of the session to avoid frustration. P13 stated that "he [C13] has hard time with attention. The length was little bit long but he seemed to enjoy it. " Overall, as P2 said about her child that "she definitely needed to do it at her own pace", suggesting that the difficulty and the length of the game need to be more adaptive to children's capabilities.

Differential effects of game repetitiveness. Some parents (8 out of 19), suggested that the game was too repetitive, leading their child to feel *bored* (P5, P6, P13, P16) while others noted it might also have *helped them build confidence* (P16) or *strengthen number concepts* (P2, P11, P17) over time. P13 said, "in the beginning he [C13] had fun. Toward the end he got bored with the repetition." and P16 said her child "was more looking forward to something new or something different." In contrast, P16 noted that "even though they know the answer, expressing themselves is challenging", and that due to the repetition "she [C16] knows what is coming up so it builds the confidence." Moreover, P17 thought that "the repetition of Misty to walk him through the instructions was helpful", especially "while he was interested." Overall, this suggests that future versions should balance variation and repetitiveness.

Effects of verbal feedback on game experience. For the conditions with verbal feedback (i.e., audio-visual condition and audio-visual-social condition), parents (P4, P6, P12, P13, P15, P17, P19) specifically mentioned that their children liked to *interact with and speak to the robot back and forth.* P6 said her child really "likes the idea of interacting with Misty [the robot]", and explained this by arguing "robots are intrinsically interesting and fun to a kid so that's something different to talk and interact with" compared with talking to a person. P12 thought that the game is "a good way for kids to be more interactive, and she liked to "have more interactions back and forth." In addition, parents emphasized that they thought their *children can play the game independently after getting used to the game*. P12 said her child "would be more independent" playing the game "after getting more comfortable" with it. P15 also supported this idea saying that "at first I think we would do it all together, but after a while it would become more independent." P17 expressed that having his child "be able to use it alone whenever he wants to would be more impactful." However, P4 thought her child felt some social pressure and stated "it is weird to play with something while people are watching", and she felt her child might "be more comfortable and willing to push through frustration" if they played alone with the robot. These findings suggest that adding verbal feedback to visual information can facilitate interactive learning and support children's independence in the game.

4.2 Family Perceptions towards the Robot

Across all conditions, most families (10 out of 19) expressed that they liked the robot and felt that the robot was exciting (P3, P5), engaging (P3, P18), real (P3, P15), fun (P6, P17), enjoyable (P2) and helpful (P3) to play with in the game. When asked to pick a facial expression to show their feelings towards the robot, most children picked the happiest face except that C6 picked the neutral one since he thought the robot is sometimes boring. P5 thought his child "particularly liked the robot" and was "definitely excited" about it, while P6 felt that the robot has "cute and fun factors." Moreover, parents described that they liked the robot because of its embodiment and real-life presence, movement, voice-command control, and interactive capabilities. For the *embodiment and real-life presence*, P15 emphasized that since "it was a robot in real life instead of an animated thing", she thought her child "felt like it was more real so he got more invested and liked seeing it move back and forth, compared to playing games on the tablet." For *movement*, P2 mentioned that her child "liked watching it [the robot] move" when playing the game and C14 said he liked the robot because "it moved." For *voice-command control*, P7 expressed that being "able to give the robot voice commands" facilitated their child's confidence and feeling of accomplishment. For *interactive capabilities*, P6 thought that "robots are intrinsically interesting and fun to a kid so that's something different to talk and interact with" compared to a person. In sum, our participants showed positive feelings towards the robot due to its affordances (embodiment and real-life presence, movement, voice-command control, and interactive capabilities), which support the idea that integrating robots in educational games can improve children's experiences.

Perceptions of robot behavior. For conditions with verbal feedback (i.e., the audio-visual and audio-visual-social condition), participants (P11, P15, P17) expressed negative feelings towards the robot due to its slow reaction in movement and speech. P17 stated that as C17 gave a command to the robot, "it takes a little longer for the robot to actually do it" or they needed to "re-prompt him," which made the child infer that the robot "could not hear him" or led him to think "he said the wrong thing." These findings suggest that an appropriate speed of movement and speech should be considered when designing a learning companion robot.

Robot's Perceived Role: Visual-only condition. Children made specific inferences on the robot's reactions, which later shaped its perceived role. According to P16, if her child observed that the robot was not moving, she would think that "maybe that's not the right number so she would calculate again" or that the robot "might not be able to hear," which made "them [children] think more" since the robot had "it's own brain too" and had "a surrounding sense and reacting to it." P16 further stressed the difference between interacting with a robot and interacting with a screen (e.g., computer, tablet), stating, "the robot would keep their [children's] mind more running than just seeing the maps [number line map] on the screen." P14 also suggested that the lack of emotion expressions made C14 feel "a little more comfortable" since the robot was an "inanimate object." Overall, in the visual-only condition, although the robot did not provide any verbal or emotional feedback, children were still able to infer the robot's intention due to its humanoid affordances, which made playing games with a robot different from playing games on a screen.

Robot's Perceived Role: Non-social conditions. For the non-social conditions (i.e., visual-only and audio-visual conditions), parents (P10, P12, P17) believed that including *social components* to the robot such as eye contact and facial expressions would have provided helpful feedback to the child. P12 thought "it would be cool and helpful" if the robot could "look at the kids and they could see the robot's face" and showed expressions such as "a light up smile or a happy face." P12 believed that children would "get more feedback" from the robot's facial expressions. In addition, P17 suggested that being able to see "the robot's face talking" would have give children a clue whether the robot is "going to say something" or it is "done saying something." Overall, families under the non-social conditions expressed a need of including social cues such as eye contact and facial expressions to support their child's engagement.

Robot's Perceived Role: Verbal conditions. For the verbal conditions (i.e., audio-visual and audio-visual-social conditions), *personalized speech* and the *scaffolding designs* were preferred (P4, P7). P4 and C4 expressed that they "liked how it would say her [C4] name" and the robot could have more encouraging and personalized speech (P7). P7 suggested that the robot's speech was "encouraging" and the child could "take another chance" in the game as her child "likes to win" in games. Moreover, specifically for the audio-visual-social condition, C4 revealed that the robot's "colored eyes" was "her favorite" part. Overall, the verbal and social cues expressed by the robot was liked by the families.

4.3 Parents' Perceptions of the Child's Experiences

Across all conditions, parents observed that their children's individual difficulties in *math skills and counting* caused them to experience some challenges during the game and they *seek reassurance of correctness from their parents*. To deal with these challenges, children used strategies such as *pointing and finger counting*, while parents used *descriptive and encouraging strategies* to be supportive.

Difficulties with basic numerical knowledge. Some parents (P1, P2, P4, P5, P19) observed that their children encountered difficulties in the game either because they did not have the sufficient foundation for number recognition skills required for the game (P2, P4, P5) or because they failed to understand conceptual number relationships (P19). For *lack of prior knowledge for number recognition*, P2 thought her child needed to learn how to recognize the numbers "before starting to adding or counting up" as she was "not there developmentally." Similarly, P4 expressed that "definitely being unable to recognize numbers was holding her back from getting it." For individual *challenges in understanding conceptual number relationships*, P19 described that his son "can count very high" however he has memorized the numbers as words and "the numbers don't mean anything" to him. P19 further explained that "figuring out how to add the numbers is the challenging part for him" and the child "can not correspond the number on the wheel and then number on the line." These findings imply that children's varying individual difficulties with basic numerical knowledge might require different scaffolding strategies that would support a variety of cognitive components for numerical skills.

Parent-child interactions around the game. Some parents (4 out of 19) revealed that their children were hesitant of expressing themselves and would keep on attempting to verify their answers with their parents, even though they had already figured it out. Parents speculated the following causes for this issue: (1) children were shy to verbalize the answer out loud (P11, P16, P19), (2) children wanted to win and get things right (P11, P12, P15), and (3) children were uncertain if something bad would happen if they get things wrong (P16). Moreover, parents explained that these behaviors could be surfacing due to (1) children's own personality (P11, P15) or (2) the pressure from being observed by parents or the experimenter in the game (P16). For feeling of *shyness*, P11 described that sometimes her child had the answer in mind but "was too afraid to say it out loud so she would whisper it to me [P11]." P19 also explained that "in general if someone is watching him he gets shy." For *intention to be perfect*, P15 said that her child "felt more comfortable asking me [P15] first", because "personality-wise he is a bit of a perfectionist," and "he wants to do the things perfectly the first time." For *feeling of uncertainty*, P16 indicated that her child "wasn't sure what would happen if something went wrong with her," so "she would look at me to get a confirmation." In sum, our results suggest that the interaction design might have caused some children to seek reassurance from their parents due to intrinsic or external pressure to be successful in the game.

Children's non-verbal game strategies. Across all conditions, most parents (13 out of 19) stated that their child used "finger counting" or "pointing to the screen and counting the squares on the number line" as a strategy for playing the game, especially in the case when the child spun a relatively larger number (i.e., 5 or 6). P3 summarized this as his child would know the answer if it is "1 more," but when "it [the spinner] was 4, 5, 6 or more... he couldn't do it if he didn't touch to count." In addition, for children who were not able to recognize numbers on the line, they would need to count from the start (i.e., number 1) up to the number the robot was supposed to go. As P4 described, his child "would hold her finger on 8 and try to count to 8 to figure out which number it was." In sum, children used pointing and counting as the main strategies to solve the game.

Parent support for child gameplay. Across all conditions, nearly all parents (15 out of 19) expressed that they used supporting strategies to help the child understand or remember the game rules (P2, P3, P4, P6, P18), to support the lack of prior number knowledge (P2, P16), to help the child develop game strategies (P2, P3, P4, P13, P19), to encourage or reassure the child (P11, P12, P15, P16, P19), and to help them learn from the game and avoid negative feelings (P4, P5, P10, P12, P16, P19) or distractions (P5, P11, P14, P16, P17, P18). For *helping children with the game rules*, P2 mentioned that her child needs "more explanations" and "an easier breakdown of what [C2] needed to do next," and P6 said that she "wanted to help clarify" for the child when he "didn't understand" or "didn't know what he was supposed to be doing." To *support the lack of prior number knowledge*, P2 thought that most of her child's failures in the game "stemmed from her[C2] insufficient abilities in number recognition," which is "the foundation of the game," and P2 felt that she "did a lot of that" to "make sure [C2] has the right numbers to go to the next step." For *helping children develop game strategies*, P2 described a scenario where the child spun a 3, P2 would say "count to three" and would move their finger as the child counted. P2 continued saying that "so my finger would be under six" and she would ask her child "what number is that?" Moreover, both P13 and P19 indicated that they had to "remind" or "help" "[the child] to count." For *reassuring children*, some parents (P15, P16) would take action to comfort their children if they seek reassurance.

P15 found herself "being involved the most" during the time when she noticed that her child "would look at me [P15] before answering to the robot," and P15 would "try to get [C15] to say it out loud." In addition, P16 described that her child feared "if something bad would happen" if the answer was wrong. P16 would assure the child that "getting a wrong answer is okay" by explaining that "we are trying to learn." When asked about the *reasons parents were motivated to intervene*, they suggested that they wanted to *avoid negative feelings or distractions*. P4 said that he wanted to help his child when he noticed that "she is at a level of frustration" to "help her keep going." Moreover, P19 said that he intervened with the game when "[C19] was not listening at all or he was being silly or I just wanted to remind him of the task." Overall, parents used descriptive and encouraging strategies to support their children.

4.4 Design Suggestions from Parents

Parents provided a range of design suggestions to improve their children's interaction with the robot. Some suggestions were observed across all conditions, while others were observed based on a certain condition. Across all conditions, parents expressed suggestions that focused on the design of visual feedback in the game , varying the types of robot's support , design of incentive from the robot , and variation of the game . The condition-specific suggestions focused mostly on the design of sensory or social feedback from the robot.

Need for more interactivity. Parents had several design suggestions for interactive visual feedback, including a pointer (P1, P2) instead of or in addition to the number frame, covering the numbers visually (P3), and changing the color of the numbers on the board (P7) to improve children's learning experiences. P1 suggested, "if there was a pointer," her child would be able to "visualize the number she [C1] should say," and that would "definitely help her." P3 suggested "visually blocking out the numbers where she [the robot] has already walked so he [C3] could sort of see that a little more." Lastly, P7 suggested that the number line have different colors and that the color change "could be designed so going past 10 could be more exciting." Overall, parents thought that interactive visual feedback could be designed to help children keep track of their progress and improve their learning.

Need for explicit robot guidance. Parents suggested that the robot could support children in more explicit ways, including providing strategies in the beginning (P10), more scaffolding (P3, P4, P14), and counting with children (P2, P14). P10 thought that "it would help in the beginning if there was some learning or strategy provided" to her child. Other parents requested several scaffolding interventions that lay out the math problem more intuitively for children. P4 wanted a *visual representation of energy from the magic spinner* so children can "see the energy fade out on Misty. Watch it go from 3 to 2 to 1", which he believed "would help them see that transfer of energy" and the "process moving forward." On the other hand, to help children who were not experts in recognizing numbers thus had challenges moving the robot, P3 suggested an *intuitive way to verbally control the robot.* She described that her child "didn't know the name for it[target number]," so "if she [C3] could just say forward, forward, forward, stop" and the robot would eventually say "Oh, I need it to go to 8," and then children would understand the numbers better. Some parents wanted the robot to *count together*, for example P2 wished the robot could say "let's count together" then would "count with her [C2]," and "move together" so that the child can follow it visually. Overall, to support children's learning, parents suggested that the robot could provide explicit strategies, show a representation of the "energy," have intuitive verbal-controls, and count together with the child.

Need for more motivational incentives. Parents suggested that additional incentives integrated to the game could be effective in motivating children to learn and play, that included a song (P11, P12), colored lights (P12), or rewarding tickets for purchasing at a virtual store (P10). P12 thought "music or lights are always exciting" and P10 believed it would be "very motivating" and "effective" for her child to earn "tickets" that allow her to "buy things" such as "clothes, toys and accessories for her [C10] avatar" in a virtual store. Overall, parents suggested including incentives that could motivate children by sharing fun activities such as songs or rewards.

Need for more variation in game flow. Parents suggested that it can be more variant regarding the difficulties of the game (P6, P13, P14) and the robot's reaction (P6, P14, P19). Moreover, small games or questions either related or not related to numbers could be provide during the game (P6, P14) to avoid disinterest. Regarding *adding difficulties to the game*, P6 suggested that allowing children to "see the higher number line" on the floor "could be helpful." On the other hand, P14 suggested that the robot could prompt the child to figure out numbers for cases that it was moving *backwards*, where subtraction could be introduced. It is a "Way to ramp up the difficulty as kids get better with it." In terms of *varying robot's reaction*, P14 thought it would "help out kids overall" if the robot could "explain in different ways" P6 added on that by suggesting "more varied reactions to what he[C6] was saying" to the robot, instead of always saying "the same exact thing." For *integrating variant games and questions*, P6 expressed that "being able to switch things up is always good." P14 added concrete ideas on this point by suggesting that the robot could "go completely off topic of math" during the game and, for example, ask children to "name an animal." Another idea from P14 was that the robot could *ask questions related to the number.* For example, the robot could ask "is 7 an even number or an odd number?" Overall, parents wanted the difficulty of the game, the robot's reaction and speech content, and the type of games and questions to be more variant.

Differential design recommendations across conditions. For *visual-only condition*, many parents (P1, P3, P5, P16) expressed that they would prefer the robot to have "voice" (P1) to "count the numbers out loud" (P3) and provide more feedback or response if the child "said the wrong number" (P5, P16). P10 expressed that it would be better if the interaction was "put it in the context of a story" that would allow the "personification of the robot" and would "motivate" the child when the game gets challenging. In addition, P10 suggested that receiving "immediate feedback" from the robot "would help her [C10] stay engaged and help her learn." For *audio-visual condition*, some parents wanted the robot to express more *social cues* such as eye contact, body gestures, and facial expressions (P3, P6, P12). P12 thought that "if Misty could look at the kids and they could see her face" that would "help them [children] get more feedback." P3 also indicated that if the robot "looked at him or thanked him [C3]," the child would feel "like he's helping her [the robot] do something." In the *audio-visual-social condition*, P4 stated that they "liked the facial expressions of the robot" and elaborated on how the child liked to be addressed by name and would like to receive more motivating feedback, such as "great job [child's name]."

5 DISCUSSION

Participants expressed positive feelings toward the robot (exciting, engaging, real, fun, enjoyable, helpful) due to its affordances (embodiment, real-life presence, movement, voice-command control, and interactive capabilities). Consistent with previous studies showing that robots can help children learn in various educational settings [1, 4, 10, 22, 27, 45], including math concept development [18, 43], our findings support the idea that integrating robots in educational games can improve children's experiences due to specific capabilities that robots endow. Embodiment and real-life presence of a robot has been considered to be an important factor in social interactions [12, 26, 28]. We observed that the robot moving with voice commands contributed to children's perception of robot's social presence, which differentiates robots from other types of media such as computers or tablets [17, 24]. One parent (P16) from the visual-only condition stated that without verbal or social feedback, the child was still able to infer the robot's intent from its stop-and-go reaction, which suggests that children attributed perception, knowledge, and intention to the robot.

Although families were excited about playing the game, their perceptions varied during the game depending on children's capabilities. Some got frustrated when the child was unable to figure out answers, some got bored when they found the game too easy or too repetitive, and some gained confidence when they experienced steady improvements over time. These differences suggest that the game needs to adapt to the child's ability, including to baseline ability and to improvements within the game, be less repetitive, and comment on a range of topics including the game. In support of the idea of an adaptive game, Janssen et al. [18] indicated that children showed higher motivation and better performances in mathematics games when they were progressing to a personal goal instead of a predefined one. Parents' suggestion of having the robot provide comments and questions that are related or unrelated to numbers during the board game echoes recommendations by Ramachandran et al. [32] that providing personalized breaks, either along with activities related to educational goals or not, enhances children's efficiency and accuracy in educational tasks. Overall, the design of interaction should be adaptive to the child's abilities and needs.

There is more parental involvement in this online study compared to typical child-robot interaction studies conducted in a lab. We involved parents as we need their qualitative feedback and observations on their child's learning experience. In addition, it might be hard to instruct the child during the remote study, and parents provided assistance. However, while some parents were involved moderately, some were highly engaged, which may potentially affect children's experience. Furthermore, a limiting factor due to the lack of audio-feedback in the visual-only condition might have also affected the amount of feedback children requested and received from their parents. Future studies should provide clearer guidance for parents in order to better harness parental involvement.

5.1 Design Implications

We first highlight the main *strengths* and *weaknesses* of each form of feedback to inform the design of learning companion robots. We then outline the design implications of robot-mediated games to support numerical skills.

5.1.1 Implications for the Future Design of Robot Feedback.

Visual-Only Feedback. Our findings indicate that the main *strength* and *weakness* of visual-only feedback is less distraction from the learning task and a lack of verbal feedback the child might seek for, respectively. In the visual-only condition, while several families suggested that they would want verbal or social feedback from the robot, the simplicity allowed children to focus on the game more and have fewer distractions from the robot. One parent (P14) argued that they liked the lack of facial expressions since it made the robot look like an inanimate object, which would distract their child less. However, this inanimate appearance can be detrimental to establishing a sense of companionship.

Audio-Visual Feedback. The main *strength* of audio-visual feedback is its support for interactive learning and children's independence in the game play, and its main *weakness* is leaving children desiring more social interaction. Overall, families liked the verbal interaction, but they also expressed a need for other social cues such as eye contact and facial expressions. Parents thought that verbal feedback increased the interactivity of the game and allowed children to play independently. As suggested by Brown and Howard [9], integrating verbal feedback contributes to moderately better learning outcomes than social interactions alone. In addition, prior work suggests that technology-mediated multisensory instruction provides environments similar to natural settings thereby increasing motivation [2, 30, 41, 46].

Audio-Visual-Social Feedback. The main *strength* of combining audio-visual feedback with social expressions is the enrichment in the learning experience afforded by the combination of verbal and social cues. The main *weakness* of this form of feedback is the potential distraction caused by the social behaviors. Although the verbal and social cues expressed by the robot was liked by the families, previous work has suggested additional considerations in designing social interactions for robots in a math learning context [23]. Kennedy et al. [23] suggested that children perform better when the robot is not highly social, compared to an overly social one, as asocial robots lead to less distraction. Further work is required to better understand the effects of social interaction in game-based math learning settings.

5.1.2 Implications for the Design of Future Robot-Mediated Number Board Games.

Our findings and some of the limitations of our study point toward a number of design recommendations. We observed that children varied in basic numerical knowledge, and different scaffolding strategies must be integrated into the game or the design of robot interaction to support cognitive and numerical skills. Therefore, our first design recommendation is to *(1) design adaptive scaffolding strategies to support cognitive and numerical skill building.* A second design recommendation is to *(2) allow children to modify game difficulty based on their capabilities and comfort level.* Children in our study had diverse capabilities, and the game modifications increased their engagement, which suggests that the difficulties and the length of the game need to be more adaptive to children's capabilities. Our data indicated that children sought reassurance of correctness from their parents due to intrinsic or external pressure, which may suggest the importance of creating a supportive environment through interaction design that alleviates pressure on children. Therefore, we recommend that designers *(3) create an environment where children are comfortable making mistakes and learning from their mistakes.*

Our findings suggest that *(4) more verbal feedback can support children's independence when playing the game.* This recommendation is based on the parents' comments that the verbal feedback made the game more interactive and supported the children's independence. The repetitiveness of the game led to boredom in some children, but others gained confidence and helpful practices, which supports our fifth design recommendation that *(5) game design must seek to break repetitiveness and introduce variation.* Finally, our game environment only included a short number line to match the numerical capabilities of our age group in a way that is consistent with prior studies in the literature [e.g., 37, 39]. However, this simplification might have limited children's perception of the game as being akin to classical number board games. We recommend that *(6) a richer game environment, e.g., including a complete map printed as a floor mat, might provide children with a more genuine game experience.*

5.2 Limitations & Future Work

Our work has two key limitations. First, the administration of the study via videoconferencing introduced a number of challenges. Some children were not able to use the mouse during the math measurement, and the parents had to click for them (P1, P2, P3, P4, P5, P7, P12, P13, and P19). Furthermore, because the parents/guardians along with the experimenter were present on the videoconferencing call it might have put pressure on the children during the study, even if the parents/guardians were not watching. Such pressure might have limited their engagement and learning of the game concepts. In addition, while having parents on the call allowed us to facilitate the video-conference call easier and lifted the technological limitations of the target age group, it might have caused unbalanced and uncontrolled parental feedback to child which may have a confounding effect on children's learning experience. Finally, administering this interactive study in an online fashion might have limited children's learning outcomes that might unique to in-person interactions. The tangible nature of the game and the robot should be tested in-person in future work.

Second, our quantitative analysis of the preliminary data for the pre- and post-experiment math measurements found no significant differences, thus these findings are not reported in this paper. The overall pattern of our preliminary results suggest that the children in our sample were already adept at the task, which might have limited the effects of the learning activity. Future work needs to recruit children that struggle with number line concepts in order to observe meaningful effects in the math measurements and improvement of skills over time. However, our qualitative findings offer insights into child-robot interaction and design implications for robot-mediated learning games. Furthermore, we did not report an analysis from the video interactions since it is not in the scope of this research. However, in future work, we plan to conduct a times-series analysis on the video-based interaction components including the game duration, number of times children played the game, received scaffolding from the parent or robot etc. which could uncover the daily-progress of children and when learning reaches a saturation over the course of the game intervention.

6 CONCLUSION

We explored how robot interaction could be designed with multisensory or social feedback in a linear number board game. We found that while the robot's capabilities enriches children's learning experiences in the game, children encountered challenges such as insufficient numerical skills, internal or external pressure, and feeling of boredom or frustration over time. The observations introduce implications for the design of robot interaction, which may support long-term interaction with young children in game-based math learning contexts. We suggest that the robot express appropriate verbal or social feedback, provide adaptive scaffolding strategies, facilitate a supportive learning environment, and introduce variations to the game with variant reactions or comments.

7 SELECTION AND PARTICIPATION OF CHILDREN

This study followed an ethical protocol approved by the UW-Madison institutional review board (IRB). Children were recruited through their parents or guardians which we contacted using organizational mailing lists. For the consent process, the experimenter first informed the family about what to expect from the study, asked the parent to fill a consent form, and then informed the child about the study and asked if the child wanted to participate in the study. The experimenter only initiated the study after obtaining verbal assent from the child. Families were informed that data will only be shared between study team members and any figure or video from the study will be anonymized before being published in order to protect the privacy of the minors. Parents were also informed that the confidentiality will be broken only if abuse or neglect was determined during the study.

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