"That Was Mindblowing": How Reading with a Social Robot Enhances Science Learning Experiences

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Abstract: Learning sciences research has demonstrated the importance of social interactions during learning to help promote deep and meaningful understanding through a process of co-constructing knowledge, but homework reading is typically done as an isolated exercise. We have developed a social robot to provide social interactions during reading activities with middle- school children, and in this study report on how interacting with the robot affected the learning experience. Our thematic analysis describes direct and indirect benefits from reading with the robot. We conclude with theoretical and practical implications of these results.

Introduction

Educational researchers and practitioners have increasingly called for a greater focus on students developing deep and interconnected understanding of content, rather than the memorization of facts and procedures. Learning sciences research has demonstrated the importance of social interactions during learning to promote this deeper learning through a process of co-constructing knowledge (Miyake & Kirschner, 2014). Yet, most homework assignments that ask students to read textbooks or other materials, used frequently in US education and in science curriculum, are typically done in isolation. Some approaches to supporting student learning at home include educational technologies that offer aids for comprehension and problem solving, but these too often focus on procedural learning and rarely include a social component. Computer supported collaborative learning (CSCL) technologies can effectively support social interactions during learning, but require coordination between learners when used at-home, that can be difficult for elementary or middle-school aged students. To benefit from social interactions while learning in homework reading scenarios, we need educational technologies capable of sharing the reading experience and providing critical social interactions during these learning opportunities when human-human social interaction is unavailable or limited. Our goal is to address this need by creating augmented science reading activities with a social robot that can provide knowledge supports through social interactions to promote deeper understanding of science content.

Theoretical Framework

Our work is guided by a socially situated or sociocultural learning perspective (Vygotsky, 1978). Research on socially situated learning demonstrates how social interactions transform activities into collaborative experiences where knowledge is co-constructed with others. Social interactions encourage students to take an active role in their learning and engage in meaningful dialogue about content. These interactions also provide opportunities for scaffolded knowledge supports that simplify or make connections within and outside of the content (Hurst et al., 2013). While working together, learners build on and explore ideas with each other that helps to connect new concepts to other knowledge, and to summarize and synthesize what they are learning (Miyake & Kirschner, 2014). In this way, learners build rich and meaningful understanding, where they have grappled with concepts

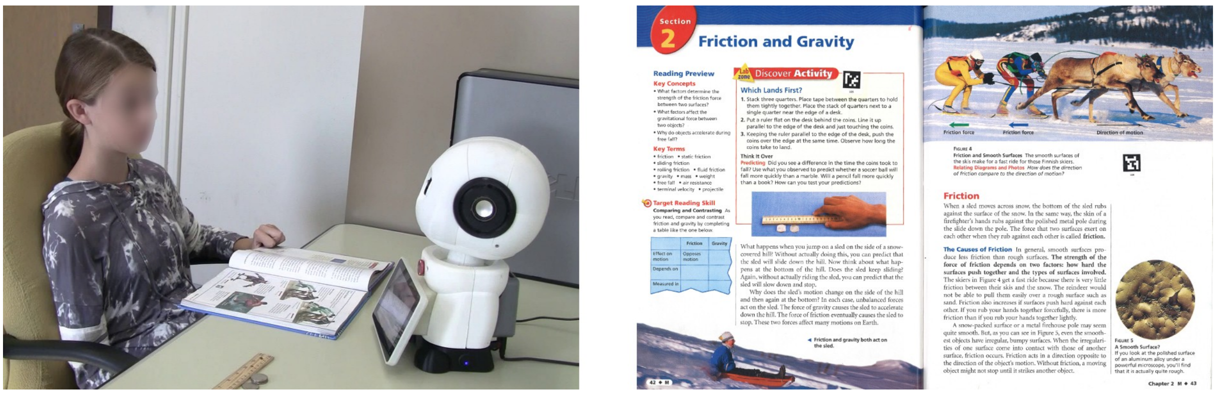

Figure 1. Child reading with Minnie (left). Textbook page with discover activity and AprilTags (right).

rather than simply tried to remember them. This social approach is underexplored in reading for learning, but some methods such as paired reading, have proven effective. Topping et al. (2011) demonstrate that paired reading, where students read out loud together on a regular basis, has long-term positive effects on reading ability that were highest for *near-peer* tutoring, where partners are close in age, and when reading pairs stopped to talk about the book every 5-7 minutes. These types of collaborative reading activities have also been found to promote greater reading comprehension in science and social studies content (Boardman et al., 2015), and can be seen as a template for creating socially situated reading experiences to improve learning.

The computer supported collaborative learning (CSCL) research community is a leader in designing technologies to support social interaction during learning (Kreijns et al., 2013). In these scenarios, the technologies, often web-based applications, are typically designed to facilitate collaboration between two or more learners, and are effective by supporting students in posing questions, exploring lines of inquiry together, practicing reciprocal teaching, and observing others learning (Stahl et al., 2014). In science learning, the collaborative supports can provide discussion boards, representational tools, or shared simulation space for learners, and can often take the form of scripts for students to guide effective interactions (Jeong et al., 2019). CSCL also has the potential to promote social interactions during reading activities. For example, elementary students participating in online collaborative readings with peers, improved reading comprehension when compared to individual reading (Vega et al., 2020), and scripted interactions between college students using an online CSCL tool enhanced their reading literacy in science content (Lee, 2015). While these technologies show promise, they require coordination between multiple learners, and therefore may not always be applied for reading activities at home and be difficult for younger learners to engage with outside of school.

In scenarios where human-human social interactions are difficult or not available, social robots have demonstrated a particularly powerful ability to make social connections with learners in ways that can improve learning (Belpaeme et al., 2018). Humans, especially children, seem to have reflexive and strong social responses to robots, where people apply and expect social norms during interactions (Ham et al., 2012). These strong social responses can be quite effective in learning environments, where robots build social connections with learners during activities (Michaelis & Mutlu, 2018), can provide meta-cognitive supports in stressful learning situations (Brown & Howard, 2014), and can inspire thinking and creativity (Gordon et al., 2015). The capacity for social robots to provide social interactions can be coupled with CSCL approaches to present socially situated learning supports. Social robots can effectively coordinate collaborative learning between human learners and can also act as collaborators themselves in learning interactions (Miyake & Okita, 2012). Social robots can act as less-able peers who need help from children to learn (Walker & Burleson, 2012), share in creating a story (Wong et al., 2016), or engage students in discussions about science (Shiomi et al., 2015). However, there is limited research on robots providing social interactions during reading activities, particularly for in-home settings.

In response to the need for work exploring the role of social robots for in-home learning, particularly as homework reading companions, we have begun a research program to explore the design of such a robot and understand the learner's experience during these socially interactive learning activities. Here we expand on findings from prior work to further our understanding of learning with a social robot during a shared science reading experience (Michaelis & Mutlu 2018, 2019). In this study, we ask the research question: *How do middle-school aged students experience learning while reading a science textbook with a social robot?*

Method

To explore the experience of reading with a social robot, we conducted a lab-based study where children read a science textbook chapter with "Minnie," a social robot programmed using design elements based on prior work (Michaelis & Mutlu, 2018). Here we report on the study procedure, materials, design of the robot's comments.

In a larger study, we recruited children from a mid-sized city in the Midwest for a randomized control trial testing the effectiveness of reading with a socially adept robot, compared to a robot without socially engaging features. Here, we examine the experience of the children in the socially-adept condition (N = 30). We chose to focus on this group since they received the maximized social interactions. Children in the study were aged 10-12 (18 male, 12 female) and had not yet started their 7th grade year. Study activities took place in a campus lab office after parent consent. Parents were compensated $25 USD for their child's participation, and study protocols were reviewed and approved by an institutional review board. Children completed a 30-minute reading session with the robot and were interviewed about their experience following the interaction. Several quantitative measures were also made during each session and are reported on elsewhere (Michaelis & Mutlu, 2019).

Minnie (See Figure 1, left) is based on an open-source 3D-printable tabletop robot, Maki, with servo-controlled head and eye movements (Hello Robo, 2020). We modified the Maki designs to add: a Rasperry Pi

3 microcontroller for enhanced computing power; a camera for image and facial recognition; and a seven-inch touchscreen display for user inputs. The robot's camera enables the use of facial recognition to track and look towards the child's face during reading, and to read scannable ID tags called AprilTags (APRIL Robotics Lab, 2020). The touchscreen display includes five buttons along the bottom, where children can select inputs for "yes" or "continue" (green button), "no" or "stop" (red button), "repeat" (blue button, "pause" (yellow button), and "help" (purple button; disabled for this study).

During the reading sessions, children read out-loud to the robot from a book with embedded AprilTags. When they encounter a tag, children hold the book to the robot's camera, and the robot responds with a pre-programmed *knowledge support comment*, that is a verbal utterance from the robot to highlight important material, summarize key points, make personal connections to the reading, or encourage children to complete activities in the book. The robot was designed to act as a *near-peer* that portrays an age and level of science understanding near the child's age and grade level. Therefore, the robot's comments were often framed as the robot wondering about a part of the book or summarizing its own understanding of what was just read. For example, after reading a section on diagramming forces, Minnie says, "Okay, I think I understand. Arrows show forces because the arrow points in the direction of the force, and a bigger arrow shows a stronger force."

Children begin by reading a custom-made introduction book that acclimates them to the reading process with the robot, and how to use the buttons and AprilTags while reading. After the introductory book, children are then asked to read a thirteen-page section, titled *The Nature of Forces*, in a middle-school level science textbook (Padilla et al., 2005) with content covering balanced and unbalanced forces and types of forces such as friction and gravity. We chose this book because it is at a reading level appropriate for our samples' age group and covers science related material typically encountered in 8th grade in U.S. middle school that our sample would likely not be overly familiar with. There were ten AprilTags placed in the reading with unique robot knowledge support comments that resulted from scanning each tag. Two of the tags were placed near two activities included in the book, and when scanned, the robot invited the child to complete the activity and say what they observed happening and why they think it happened. The first activity, the *at-home activity* had the child balance two playing cards against each other so they would stand, as in a house of cards, then exert a force on one of the cards, and explain the role of unbalanced forces in what happened. The second activity, the *discover activity* (See Figure 1) instructed children to push two different sized stacks of quarters off their table at the same time to observe which falls faster. Both stacks should fall at the same rate, and to ensure children saw this clearly, the robot is programmed to comment after the activity that both stacks of quarters fell at the same time. All activity materials were provided for the child, and they were allowed to complete the activity as they saw best.

Interviews (10-15 minutes in duration) were completed after the robot interaction, followed a semi-structure qualitative interview protocol (Blandford, 2013), were video recorded, and later transcribed verbatim. We then conducted a Thematic Analysis to analyze the data (Braun et al., 2018). Two researchers, including the first author, first familiarized themselves with the data where they reviewed and created notes from the videos. We then generated semantic codes closely related to the data using an inductive approach and organized the data within major categories based on these codes, including supporting knowledge, supporting interest, and social interactions. From these categories we then iteratively proposed, constructed, and refined emergent themes based on meaningful patterns in the data. The findings below are presented according to these themes.

Results

After several rounds of thematic analysis, we found that children felt the robot supported their learning and improved the depth of their understanding along three major themes, where the robot: (1) helped them slow down and focus on the reading, (2) provided summaries and guided attention to important parts, and (3) worked with them on the activities. Each theme is described below with quotes from participant interviews using participant IDs (e.g. R34). For clarity in reading quotes, ellipses were added to connect ideas in the responses, bracketed words indicate intended objects, and interjections were removed when not impacting the meaning.

Theme 1: Children slowed down their reading and focused more

Children felt that reading with the robot made them slow down and focus more on their reading in ways that helped them think more deeply about the content of the book chapter. In particular, children told us that reading to the robot helped them to slow down and focus so they could: (1) help the robot understand the content, and (2) think more deeply about what they read since they knew the robot would comment about it.

Children often said they learned more from reading out loud with the robot, because it slowed them down, and that slowdown helped them feel more focused on the reading. Most children directly related slowing down and focusing to the presence of the robot, as R36 told us, “If you were just reading aloud to yourself you might kind of slip over everything and say it fast.” The idea of ordinarily skimming through textbook readings was brought up by several other children. For example, R2 told us that without the robot they “sometimes might skip a line”, R50 said “if I was reading it on my own I might have skimmed it and skipped over some important things,” and R64 told us, “when I’m reading alone, I normally just pretty much skim the concept.” Slowing down and not skimming the text was related to children feeling more focused on the reading. Children said the robot “focused me more” (R2), “helped [me] stay on task” (R10), helped them “concentrate” (R18), or that without the robot they “wouldn’t have paid much attention (R16).” R64 further explained that they didn’t skim with the robot, because, “if you’re reading to people, they would want you to slow down so I just kind of did that to the robot.”

These responses help us recognize that the robot’s presence and interactions seemed to drive children to read more slowly and focused in two ways. First, children told us they felt they should read clearly and thoughtfully so the robot could understand the content. For example, R64 said they slowed their reading down because they, “didn’t want to be confusing, and I wanted [the robot] to learn.” This slowing down for the benefit of the robot seemed to be linked to feeling that the robot was listening to them, as R50 illustrates by saying the robot is, “someone who seems like they are listening to you read it, so. . . it sort of depends on you that they can understand it.” Second, children seemed to anticipate the robot’s comments as a sort of query, that compelled them to spend more time focusing and thinking about what they read. Children felt they had to “think about what you were reading to respond to the robot (R14),” or that the “robot might ask me a question so I thought about it more (R16). Some children felt the robot would check on the child’s understanding, in ways that were also beneficial to the robot’s understanding – that the robot “sort of checked in for herself” (R50). Perceiving these interactions as ways to stop and think about what they were reading and to learn along with the robot appeared to drive a sense that they were understanding more, as R14 said it “makes you think deeper about the book.”

Theme 2: The robot provided summaries and guided attention

As part of the creation of our knowledge support comments, we intentionally created robot comments to correspond with challenging or important parts of the text, or that directed children to consider the figures and side-panels in the text that might otherwise be ignored. Almost every child in the study discussed these knowledge support comments as helpful for their understanding, and many suggested they felt the: (1) robot explained difficult ideas in the text, (2) comments often answered questions they had or gave them time to think about the reading, and (3) robot guided their attention to important parts of the reading.

Describing the robot comments as explanations or summaries was quite common. Children said the robot, “explains things you just read” (R4), “reviewed” (R28), gave a “reminder of what you just talked about (R48), “gave you a recap that sticks in your brain” (R20), or “makes sure you know and grasp the concept” (R64). Children revealed that they often faced challenges in understanding the concepts in the reading that the robot helped with, as R26 told us “I would read like two entire pages and then she’d say a quick summary and it helped me figure it out more easily, because sometimes I’d read this really in depth thing and then [feel] like ‘wait what just happened.’” R02 also added, “if I didn’t understand something, the robot would just break it down simply and that helped.” This was a very common response, where children felt that after reading the somewhat dense material in the textbook, they benefitted from the robot’s comments that explained the concepts.

They also felt that the robot’s knowledge support comments provided a summary or review of concepts that often served to answer questions they already had, or even “confirm your thinking was right (R10)”. R8 told us “it’s almost like you can ask questions, in a way, so it’s like she answers your questions.” R10 said, “sometimes it says something that you were kind of thinking in the back of your mind, but you weren’t really noticing it. And then [the robot] kind of helps you understand it a little better.” Through these explanations, the robot seemed to help clarify challenging ideas and bring the concepts to the forefront of their thinking. There was also evidence that children felt these knowledge support comments could either clarify or confirm their understanding and anticipate their questions, as R26 told us, “I had the question before the book asked the question, and I was like oh yeah I was thinking that too. And then [the robot] explains it.” Having the robot there to provide these supports appeared to be important to the children, as R44 summarized, “usually if something was hard in the book. . . you would have to figure it out by yourself but the robot. . . helped out.” There seemed to be something specifically important about the moment after each comment for the children to think about the material. They often described benefitting from thinking for a moment to absorb what the robot had said. R6 told us after the robot, “made a comment then [I] just paused and thought about what it said, and got more stuff,” and R8 said that when they were confused, “after a comment, you’re like ‘oh, hey, that’s how it works’.” R36 said, after a comment, “I thought about everything she said and then I could remember it more.” It appears that children experienced the robot comments not only as supportive information, but as targeted answers to questions and opportunities for thoughtful reflection.

Finally, some children suggested the comments guided their attention. R60 told us the, "robot pointed out things when they were saying something that I might have missed," and R58 felt the robot "pointed stuff out to me that I didn't really see." For R16 the robot drew their attention to figures in the book as ways of talking about real life examples. Specifically, R16 felt the robot used the example of racing reindeer in a book figure (See Figure 1, right) to explain how the "reindeer were a greater force than the friction, so they were moving." This comment from the robot was particularly helpful for the child since they had "just kind of glanced over [the figure], but then [the robot] mentioned it." R58 agreed that "the picture [of the reindeer] was a good example" of pointing things out. We were intentional in designing some of the robot comments to refer to figures in the book, and it seems that these references helped children who may have otherwise missed those pieces of the reading.

Theme 3: Working with the robot on book activities were powerful interactions

Another area where we deliberately designed comments to point out parts of the textbook reading to children, were the two activities contained in the book chapter. These seemed to be experienced by the children as opportunities to work with the robot on the content, and were appreciated as moments of interactive learning that they would have otherwise skipped – often resulting in powerful moments of understanding. Although the robot only made comments before and after the activities, children felt that these were interactive experiences. They felt that they were, "learning more," by "doing the tasks with [the robot] (R06)", and because they "actually have to interact with [the robot] (R64)." Doing these activities with the robot helped R14 "feel more involved." R64 said they had to "do little projects that you normally wouldn't do. . . you would talk to [the robot] and explain it." The notion that children might not ordinarily engage with the activities was also mentioned by R24, who said they "normally don't do the activities at home," but they "helped with being stumped." This interactivity appeared to help children feel they were working with someone else to make connections and think critically about the content in the text. R32 told us that when the robot's comment matched what they saw during the activity, they "understood it more and I felt like somebody else had the same opinion as me." The impact of these convergences of ideas was very clearly articulated by R20 in the following exchange about their experience doing the at-home activity in the book:

> *Researcher:* I noticed that at the end of the book, when you started reading about air resistance. . . you said, 'Oh, that's why they fell at the same time,' and you went back, and kind of picked up the quarters and looked at them again. Can you tell me about that, like where that sort of connection came from?
> *R20:* I thought that it was supposed to be connected because they did one and that [the quarters] fell at the same time and that they didn't do what I expected. It was, just mindblowing.
> *Researcher:* Did you notice, did you see that they fell at the same time on your own? Or did you. . . because the robot also has a comment that sort of makes sure that you do see that they fall at the same time. Sometimes people sort of miss that. Did you figure that out on your own, or did the robot kind of help you see that, or did you remember that?
> *R20:* I didn't and then I thought I did it wrong because you're not used to doing that, and so then I scanned the page and I did it one more time, I heard the robot's comment and then I'm like woah, that's actually what it's supposed to do and I'm like woah, that was mindblowing.

Here R20 demonstrates how they connected the comment the robot makes, explaining why objects with different masses fall at the same rate, to their experience with the at-home activity. The robot guided R20's understanding and strengthened this understanding with a later explanation. R20 described the robot making this connection as "mindblowing," that indicated help from the robot to connect ideas across the reading was very powerful. This exchange helps to summarize how children saw the benefit of their reading with the robot. The robot seemed to do more than simply provide supports for their reading, but rather provide a socially rich interaction.

Discussion

In this study, we sought to further our understanding of how children experience science learning with a reading companion robot. The results from our semi-structured interviews with children after reading with the robot demonstrate that the robot: (1) created a sense that the learning experience was for both the child and robot that helped focus the child's efforts; (2) provided targeted supports that anticipated the child's questions and guided their learning; and (3) participated in interactive knowledge building to help children think clearly and deeply about the content. Involving a social robot in science reading activities may be a powerful tool in re-imagining these reading activities as socially interactive rather than isolated. While there is evidence that children have strong social responses to robots (Ham et al., 2012) and that there are learning benefits to working with a robot (Belpaeme et al., 2018), there are currently no studies to examine how children experience reading science content with a robot. We believe evidence from our study suggests that the social presence of the robot transforms the reading experience into a shared knowledge building activity between the child and robot, that extends beyond the scripted knowledge support comments of the robot. Children found that the presence and demeanor of the robot encouraged them to utilize better reading habits (i.e. slowing down, focusing, and thinking) that benefitted their learning. They also described the reading as interactive, where they felt a constructive back and forth in grappling with the concepts in the book, particularly in completing the discovery and at-home activity in the book.

These findings provide a unique perspective on our understanding of child-robot learning interactions. To strengthen learning sciences theory, we provide demonstrate how children experience reading interactions with a robot, how knowledge can be co-created with an artificial partner, and how socially appropriate and meaningful interactions are key to creating powerful co-learning experiences. We believe our findings also illuminate practical implications for integrating these interactions into class and in-home learning experiences, and illustrate the aspects of the reading interactions that might best be leveraged for deepening science learning. Here, we discuss how our results support and expand prior work and share practical implications of science learning with a social robot.

Social robots provide socially rich experiences to scaffold and co-create knowledge

Empirical evidence from learning sciences research has demonstrated the benefits of social interactions during learning. Social interactions provide supports or scaffolds for learners that aid their understanding of concepts or that allow them to work on problems or material they might not otherwise be capable of doing alone (Vygotsky, 1978). Social engagement provides meaningful and natural interactions that promotes depth of thought about the content and builds deep and interconnected knowledge by co-constructing knowledge. The findings from this study demonstrate how the social presence of the robot directly and indirectly enhanced the learning experience.

Learning new concepts can be a tremendous task for novices, and these learners tend focus on the surface features and basic ideas they are grappling with, rather than complex or integrated knowledge we strive for in modern educational contexts. Our findings demonstrate that while children were reading the science textbook, they felt that their interactions with the robot allowed them to think more deeply and better understand what they read. For example, R10 told us the robot sometimes, “says something that you were kind of thinking in the back of your mind, but you weren’t really noticing it.” In this way, the robot’s comments helped children articulate and connect their ideas. While sharing this reading experience, children attended to new concepts, but often weren’t able to fully grasp the themes and bigger ideas of the reading. The robot provided summaries or pointed their attention to key aspects of the reading to aid their deeper thinking. The inability of learners to contend with the complexity of new content has been demonstrated in prior learning science research, and there is strong evidence that suggests learners benefit from social interactions in working on new material (Miyake & Kirschner, 2014). Our findings are in line with these theoretical perspectives, and add to this body of work, by demonstrating that children have a natural inclination to embrace a social robot as a near-peer, and that children feel these interactions are beneficial to their deeper understanding. Learning theory also suggests scaffolded supports can simplify or highlight connections and complexities within the content and relate new ideas to other knowledge and concepts (Puntambekar & Kolodner, 2005), We expand on this theory by demonstrating the benefit of providing these scaffolds in a social context. Our robot often used traditional scaffolding techniques, such as summarizing and guiding attention to a key figure, in a conversational way, within the social context of learning with the child. Scaffolds that summarized concepts were delivered as if the robot had just understood the material and was now summarizing their understanding, rather than presenting the summary as simply a fact for the child to absorb. We believe the robot’s social presence was key in providing direct supports for children.

The social presence of the robot also seemed to provide context for children to feel as if they were *learning with the robot*. Learning socially with the robot presented indirect benefits to the learning experience, where children slowed down their reading, focused more and read clearly so that they and the robot could better understand. At no point were children instructed to behave this way. Rather, our findings suggest these indirect effects came from children feeling that they were learning together with the robot, which seemed to cause them to subsequently change their typical reading habits to conform to the social context. This benefit is in line with prior work on the benefits of group learning to co-create knowledge (Miyake & Kirschner, 2014). One important element to induce the effect of learning together seemed to be that our robot’s personality was designed to be a near-peer (i.e. at just about the same ability level), rather than a tutor or teacher. Children felt the robot needed the child to help it learn, and wanted the child to think about the reading so the child could engage with the robot's comments (that were often seen as questions). That the robot could instill this sense of co-learning with such limited interactive capabilities demonstrates how willingly and naturally children embrace such a learning paradigm. We believe we provide evidence that the social presence of the robot had the indirect benefit of transforming the learning experience into a more meaningful and deep exchange of knowledge that stems from our natural ability to build on one anothers' ideas and work to achieve mutual understanding.

Practical implications: augmenting learning using social robots

Our findings suggest that learning with a social robot can enhance the learning experience and transform a reading activity into a socially meaningful interaction. These findings have practical implications for learning with robots in both in-home and in-class settings, and offer some nuanced details of design and implementation decisions that can best facilitate the social learning experience. First, in creating direct learning supports, it appears that interactive activities interspersed throughout the reading may provide important learning opportunities, and also provide key moments for the robot to refer back to. Our reading included two such interactive activities, where children were asked to try balancing forces with playing cards (the at-home activity), and to observe the rate of falling for different masses with similar shapes (the discovery activity). In both of these activities, the robot asked the child to summarize their thinking and explain what they saw, which encourages the child to reason about these concepts. Since children often told us they would ordinarily skip these, the request from the robot seemed to be important to encourage them to engage in and think about the activity. The robot also referred back to these activities during the reading to help connect ideas, but also to enhance the importance of engaging in the activities. Second, the robot's design appeared to indirectly impact the learning experience by triggering social norms and expectations from children. The robot comments being interspersed throughout the reading seemed to emulate an interactive reading style that fostered the co-creation of knowledge, where children were compelled to focus, read carefully and take time to gather and synthesize their thoughts about the content. Our knowledge support comments did not deliberately ask children to slow down or think deeply, but there seemed to be an indirect effect of the social context that encouraged children to do so. The near-peer perspective of the robot may have enhanced this effect as children attributed the robot's need for understanding as a reason they read more carefully. We also found many children thought the robot anticipated their questions or was even asking them questions, as the robot provided comments that related closely to challenging aspects of the text. Our robot was not technically capable of such enhanced interactions, but the child still felt they needed to read more carefully to engage with the robot. These observations show how social supports enhance the experience, but improvements to the interactive capability of the robot, including asking and responding to questions may also be required.

In summary, based on our observations of the benefits to the student's learning experience, to promote deeper thinking while engaging in science reading we suggest designing robot interactions that: (1) provide opportunities for interactive activities during science reading, (2) allow time for the child's thoughtful reflection, (3) include robot references back to joint activities and previous learning, (4) utilize a near-peer perspective for the robot, and (5) closely tie robot comments to critical and complex parts of the reading. These supports can benefit in-class activities, where a robot might guide individuals or a small group, as well as in-home learning, where a robot can become a homework companion that encourages active engagement with content. The positive effects of these designs can be achieved with a relatively low-tech robot, but sustaining positive interactions over time may require enhanced capabilities such as posing and responding to questions.

Conclusion

In this study, we explore children's experience of reading with a social robot, and these experiences inform designing learning technologies. This approach limits the scope of our interpretation, in that we cannot report causal effects between these experiences and learning. We are also limited in that we do not include a comparison to other learning technologies or to reading on their own, and therefore cannot determine the scale of the effect of reading with a social robot. Finally, the short duration of the reading limits understanding how these interactions may change over time. For future work, we plan to examine science reading with a social robot in the context of school-based homework, over time and compared to other interactive learning technologies. During these studies we will conduct quantifiable measures of learning and estimates of changes in interest over time.

In summary, these findings demonstrate reading with a social robot creates a social learning experience that children feel encourages them to think deeply and engage meaningfully with science content. These findings support the growing belief that social robots can be a powerful tool for learning, and the social nature of the interactions can enhance student learning in tasks, such as reading, that may otherwise be isolated.

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