HUMAN-ROBOT INTERACTION

Reading socially: Transforming the in-home reading experience with a learning-companion robot

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Social robots hold great promise as companions and peer learners for children, yet little is known about how they can be best designed for this population, what interaction scenarios can benefit from their use, and how they might fit into learning activities and environments. We aimed to close this gap by designing a learning-companion robot to augment guided reading activity and examined the robot's impact on an in-home reading experience. In this paper, we compared the experiences of early adolescent children aged 10 to 12 years (N = 24) who completed guided reading activities either with a learning-companion robot or as a paper-based activity in a 2-week-long, in-home field study. We found similar reading frequency and duration in both conditions and that both guided reading activities were described as positive experiences that helped to build reading skill and to sustain engagement. Children who read with the learning-companion robot further reported that the activities supported reading comprehension and motivated them to read and indicated a deepening social connection (i.e., companionship or affiliation) with the robot. We conclude that, rather than the activity falling off after a novelty effect, our simple prototype social robot is capable of preserving the benefits of an existing in-home learning activity while transforming the reading experience into a valuable, social one. Our findings contribute to an understanding of how we might capitalize on the capacity of social robots to serve as a transformative learning tool as robots become more widely available to the public.

INTRODUCTION

Social robots have the potential to transform learning by supplementing learning activities, particularly at home, yet how this potential might be realized is unknown. Social interaction benefits learning by shaping cognition (*1*), comprehension (*2*), and the development of an identity (*3*) and interest (*4*) in academic activities and topics, including reading (*5*). This socially situated learning is typically present during classroom interactions with peers and teachers but is often lacking at home. If social robots can transform an in-home learning activity into a dynamic social activity and are capable of imbuing their interlocutors with a sense of social companionship and affinity (*6*), which we refer to as "social connectedness" (*7*), human-robot social learning may be especially effective for children as they develop reading and literacy skills. Commercially available robots are becoming widely accessible, but their use in learning applications is largely confined to classroom learning in programming and robotics (*8*), and their long-term use is rarely studied (*9*). Thus, social robots remain an underutilized and understudied resource for in-home socially situated learning support, which leaves an important gap in the research literature.

In-home reading is an important part of developing skills such as fluency and comprehension (*10*), and reading practice benefits from socially situated learning supports (*5*), yet in-home reading practice is often an isolated activity. Reading socially can transform the experience into a collaborative activity where shared knowledge construction aids reading comprehension—the process of constructing meaning from text (*11*)—by both distributing cognitive processes among group members and generating connection-making and new ideas that result from the social interaction (*12*). Thus, reading comprehension improves because a social other is performing part of the cognitive activity required for comprehension (e.g., summarizing) and because new understandings of what is being read emerge from the interaction. Children can also benefit from a social other that models effective reading habits, such as making predictions, integrating prior knowledge with what they read, and processing or summarizing text during short breaks in reading (*13*, *14*). Modeling that occurs during social reading can be done by demonstrating and reinforcing these effective habits that support reading comprehension (*15*).

By middle school, attitudes toward reading decline (*16*), and few children voluntarily choose to read outside of school (*17*). To improve the development of long-term personal interest in academic areas such as reading, researchers recognize the importance of social supports (*4*, *5*, *18*). Although catching a person's interest can lead to increased engagement and positive feelings in the moment, properly holding a person's interest by promoting positive feelings, value, and knowledge for the content will lead to sustained engagement over time that develops individual interest or predisposition to independently reengage in the activity relating to the content (*19*, *20*). The effect of holding one's interest is more powerful if the learner is given ways to build relationships, share values in common with others who engage in the practice (*21*), and feel a sense of social involvement (*22*). In this way, social others can support a child's interest in reading by suggesting new reading materials, reading or listening to the child during the activity; interacting with the child and discussing the content of the reading; and emphasizing the value of their reading (*23*, *24*). These supports help develop interest, because children gain knowledge and skill in reading and begin to value reading themselves through a natural inclination toward internalizing the values and beliefs of social others (*25*).

Providing a social robot as a learning companion for children to augment in-home learning activities, such as reading, can capitalize on the benefits of socially supported learning. Developing the type of

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Fig. 1. Minnie and study materials. The learning-companion robot and the study materials, including the *Talking with Minnie* book, RFID cards, and books augmented with AprilTags. The robot's camera, the red circle on the upper torso, is used to read AprilTags and to track the child's face. A microphone, visible to the right of the camera, is used for audio-recording sessions, and an RFID reader, below the camera, not visible, is used to recognize cards for simple commands.

social experience needed to promote interest requires a social robot capable of cultivating a long-term social relationship (i.e., establishing and maintaining a social presence over time) with a child. Research in human-robot interaction has demonstrated the potential for robots to establish a strong social presence, particularly with children aged 9 to 12 years (*26*). A basic tendency for anthropomorphism (ascribing human traits to nonhuman entities) based on the robot's appearance (*27*), a reflexive application of social rules (*28*), and a reliance on social models to interpret complex interactions (*29*) may be responsible for the ease of simple social reactions to robots. Research on social robotics has also demonstrated that developing a strong or lasting social connection requires appropriate and natural social behavior, such as body orientation, eye gaze, and speech patterns (*30*, *31*). Social interactions with a robotic partner can lead to social connections and, if executed properly, can be interpreted by human interactors as emotions or feelings. Because emotional expression is an essential aspect of social interactions and connections (*32*), the perception that a robot has emotions can indicate a deeper and more enhanced social connection between a human and a robot (*29*, *33*).

Social connection with a robot can also be hindered by several factors. First, a social connection with a robot can be undermined when the robot's capabilities and functionality do not meet the expectations of the human interacting with it (*34*). This disconnect was found with the Paro robot, where researchers believed that limitations to the social connections with the robot were caused by some participants desiring to place the robot in water or approaching the robot cautiously because of its appearance as a baby seal (*35*). Social connections may also be limited by a novelty effect of working with technology where, after a brief period of time, generally one to two interactions, engagement with the technology can drastically erode (*36*). The novelty effect has been well established in human-robot interaction research, and researchers suggest controlling for its effect by allowing participants time to interact with a robot before they begin collecting data for a study or intervention (*37*).

Prior work in applying social robots to learning settings demonstrates their potential as supplemental tools to support learning (*38*). These works have provided evidence that working with a social robot can improve preschool literacy (*39*) and vocabulary (*40*, *41*) and that enhancing the social experience (e.g., providing a more expressive and natural voice) can have greater learning outcomes (*42*). Jones *et al.* (*43*) designed a robot to encourage a socio-emotional bond between the child and the robot from empathetic reactions to student affective states while performing geography tasks in a classroom. Kasap and Magnenat-Thalmann (*44*) demonstrated that robots that exhibit memory of previous interactions in a laboratory setting maintain engagement and increase social presence over time. Kanda and colleagues (*45*) initially found declining interaction between Japanese children learning English and their classroom robotic tutor, Robovie, but later observed sustained long-term interaction when the robot called the children by their names, expanded its behavioral repertoire over time, and shared personal feelings and opinions during interactions (*46*). A review by Leite *et al.* (*9*) suggested several guidelines for developing social robots for long-term use that include identifying users, recalling previous interactions, incrementally disclosing personal characteristics and novel behavior, and personalizing interactions based on the user and prior interactions. Although these studies provide design guidelines and demonstrate the promise for long-term interaction with social robots, to date we know of no such study of an academic activity, such as reading, has been conducted in an in-home setting over time. In this study, we address this gap in the literature and ask the following research questions:

RQ1: How does the experience of completing guided reading activities change when facilitated by a learning-companion robot?

RQ2: How does the experience of working with a learning-companion robot for in-home reading change over time?

Design of the social robot

To investigate these research questions, we used a social learning-companion robot, Minnie [see (*47*) for more details]. The robot significantly extends an open-source robot design from Hello Robot called Maki. Minnie has a 13.5-inch-tall body, including a static torso with an embedded camera and microphone and servo-controlled moveable head and eyes (see Fig. 1). The main interaction with the robot involved children reading out loud from 1 of 25 specially tagged books (provided by the researchers for the study) to the robot. Children first read an introductory book during their initial interaction with the robot, where they learned how to input commands such as "continue" or "stop" by scanning one of four radio-frequency identification (RFID) cards and to display visual tags, specifically AprilTags, embedded in each book to Minnie. Scanning one of the embedded tags prompted Minnie to make a preprogrammed verbal comment, through speakers placed in each ear piece, that specifically applied to what was occurring in the book.

Minnie's behaviors were designed on the basis of nine evidence-based design guidelines (see Table 1) from current interest development and human-robot interaction research. During the interaction, Minnie used facial recognition to locate the child, shifted its gaze to establish eye contact, incorporated semirandomized idle movements to achieve a more lifelike appearance, and averted its gaze when speaking to appear thoughtful (DE6). Minnie began each reading session by reminding the child of their previous book and last page number (DE8), and the child could then choose to continue reading, change books, or select a new book (DE1). Minnie provided tailored book recommendations to the children as they chose a new

Table 1. The design elements of the social robot. Guidelines from research on interest development and human-robot interaction used in the design of the robot. Learning supports provided by the robot are indirect and, rather than targeting a specific mechanism or learning outcome, are in service of enhancing the social presence and effects of the robot.

ID	Design guideline	Source of evidence
DE1	Providing students with autonomy in activities and choosing educational materials	(*53*)
DE2	Setting and monitoring reading goals	(*54*)
DE3	Providing materials that align with student topic interests and ability and support skill development	(*55*)
DE4	Providing a social partner that demonstrates interest in the reading activity	(*23*)
DE5	Reading out loud to a social partner	(*56*)
DE6	Having the robot maintain eye contact when speaking and averting its gaze while it is "thinking"	(*31*, *57*)
DE7	Providing tailored recommendations for content	(*58*)
DE8	Making references to previous interactions	(*36*)
DE9	Incorporating personal information, feelings, and beliefs into dialogue over time	(*46*)

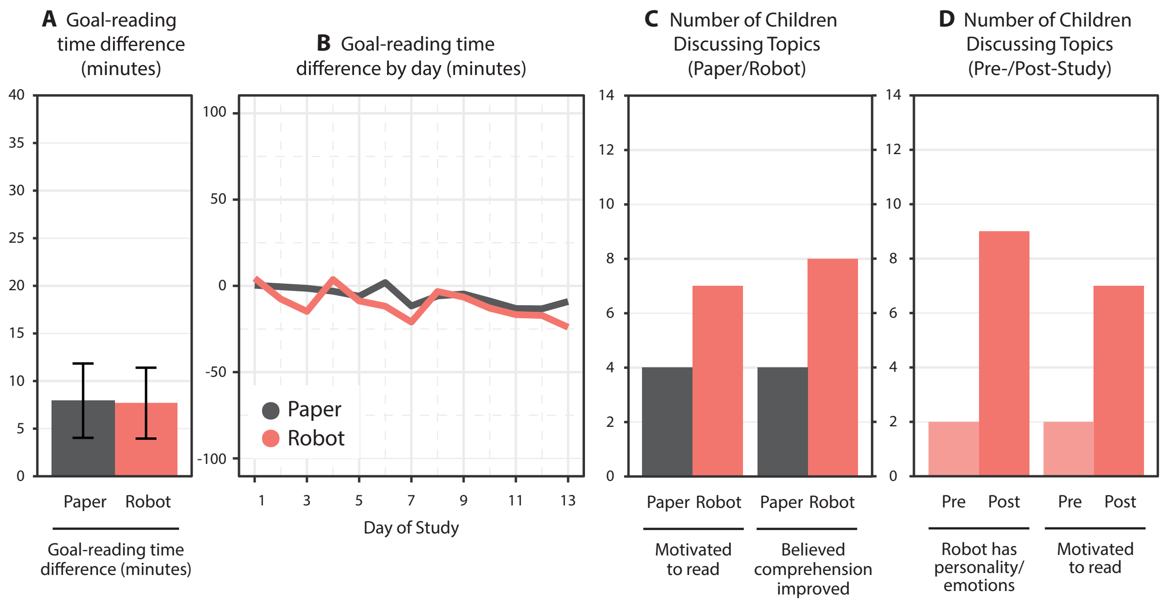

Fig. 2. Summary of results in synopsis. Reading goal to reading time differences on average (**A**) and over time (**B**). (**C**) Differences in reporting motivation to reading and improved reading comprehension. (**D**) Feelings, based on pre- and post-interview responses, that the robot has emotions and in motivation to read for the robot condition. Error bars in (A) represent SE.

book (DE7) and set and updated reading goals (DE2) based on information on the child's interest in reading, reading ability, and normal reading duration; topics that the child enjoyed reading about; and the child's reading habits during the study (DE3). The child could choose to pause or quit reading at any time (DE1), and the robot provided an update on the child's reading goal progress at the end of each session (DE2).

Minnie was programmed to make comments about the books as the child read out loud (DE5). These comments were used to convey speech that may be perceived by the child as the emotional responses, feelings, or personal history of the robot, which we refer to as the robot's emotions, feelings, and history throughout this paper for simplicity. The comments were designed to demonstrate enjoyment and interest in the reading (DE4), to summarize and predict the activity in the books (DE3), and to portray emotional responses and feelings or to convey some connection to Minnie's fictitious personal life (DE9). Before and after reading activities, Minnie told children that she enjoys reading with them, learns from their reading, and looks forward to reading with them again. During reading, Minnie used more than 600 unique comments tailored to the reading at specific pages of the 25 books included in our library. Without being repetitive or predictable, she slowly wove elements of her personality and backstory into the interactions. That is, it took time to get to know Minnie, which may help sustain and deepen social connections over time. Examples of how each design element was implemented are provided in table S1.

Field testing of the social robot

The current study examines how an in-home learning-companion social robot influenced the reading experience of children during a guided reading activity and how this experience changed over time. We chose a reading task similar to reading practice activities

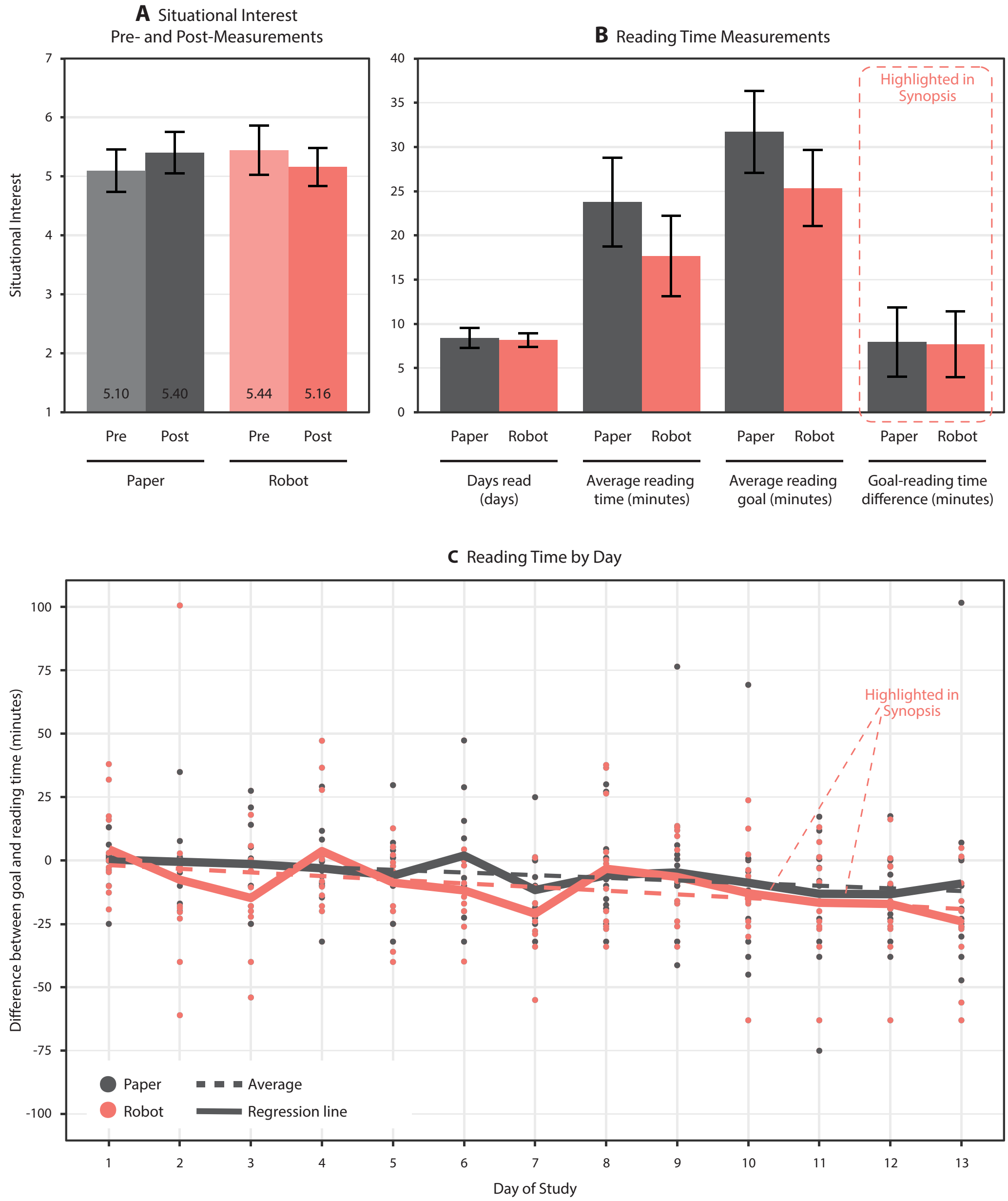

Fig. 3. Quantitative results by condition. (**A**) The average number of days read, reading times, and reading goals, as well as the average difference between the reading goal and time. (**B**) Initial and post-situational interest scores. (**C**) Reading times compared with reading goals by day, where each point represents the time read subtracted from the reading goal time for each child on each day. Solid and dashed lines plot the average difference of reading time and reading goal for each day and the smoothed regression lines, respectively. Error bars represent standard error, and values shown at the bottom of a bar represent means.

that might be assigned to early adolescent children as homework by a teacher to improve fluency. We created a guided reading activity, where children in two study conditions set and monitored daily reading goals and were asked to read out loud from 1 of 25 fiction and nonfiction books provided. The activity was either completed by children as a reading log in a paper-based activity (control condition) or facilitated by our learning-companion robot (robot condition). To examine differences in the reading experience over time, we randomly assigned children aged 10 to 12 years to one condition for a 2-week-long field study conducted at home during their summer break from school (summer of 2017). To simulate voluntary summer reading activity, we told children to read at their own discretion and that there would be no consequences for not reading.

In this study, we used a mixed-methods reporting of the reading experience. We first compared quantitative measures of the number of days read of the 13 full days that children had the robot or paper-based activities in their home, their daily reading time, and post-study situational interest in the reading activities. We then considered qualitative data from interviews after an initial introduction to the robot or paper-based activities (pre-interview) and a follow-up interview after 2 weeks of completing activities (post-interview).

RESULTS

Synopsis

During the study, reading with the robot appears to not have succumbed to a drastic drop in activity, potentially after a novelty effect wore off, but rather it facilitated sustained reading activity equally as well as the paper-based guided reading (see Fig. 2, A and B). We also found that more children felt motivated to read and improved reading comprehension with the robot (Fig. 2C), and at

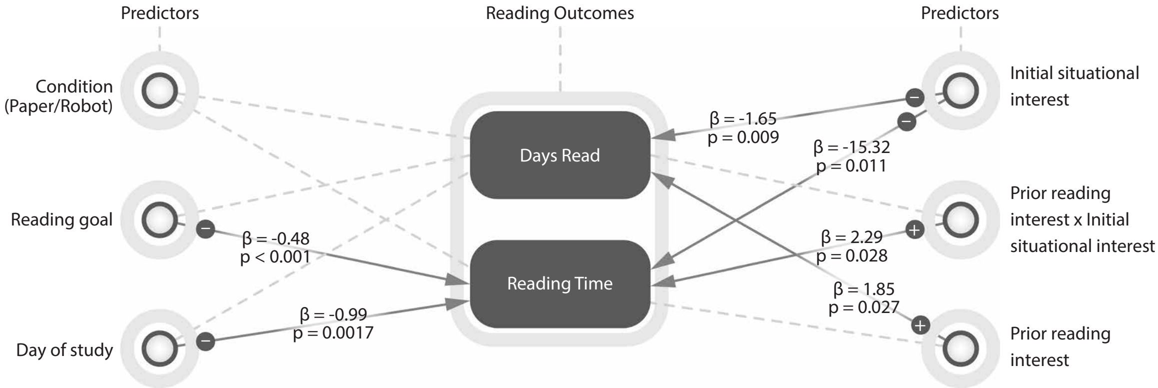

Fig. 4. Regression analysis summary. Center and outside nodes represent outcome and predictor variables used in the regression models, respectively. Solid lines with arrows and dashed lines represent statistically significant and nonsignificant contributions, respectively.

the end of the study, more children expressed motivation to read with the robot and that children felt that the robot had emotions or a personality (Fig. 2D), indicating a transformation of reading into a social activity that scaffolds key dimensions of interest development, including motivation and comprehension.

Quantitative results

Children in the robot condition read, on average, 8.17 days (SD = 2.82) for 17.67 min (SD = 15.08) per day, with a reading goal of 25.35 min (SD = 13.80) each day. For those in the control condition, we found that they read, on average, 8.42 days (SD = 3.78) for 23.76 min (SD = 17.36) per day, with a reading goal of 31.71 min (SD = 16.48) each day. There was no significant difference between groups for number of days read ($t_{22} = 0.18$, $P = 0.86$), average reading time ($t_{22} = 0.89$, $P = 0.35$), average reading goal ($t_{22} = 1.02$, $P = 0.32$), or reading time compared with goals ($t_{22} = -0.05$, $P = 0.96$) (see Fig. 3B). Figure 3C shows the average difference between reading times and reading goal for each day separated by condition.

A situational interest measure after the child's first interaction with the reading activities (initial situational interest) and a measure after they had completed all study activities (post-study situational interest; see Fig. 3A) revealed no significant difference in initial situational interest between the robot condition [mean (M) = 5.44, SD = 1.45] and control condition (M = 5.10, SD = 1.25; $t_{22} = -0.63$, $P = 0.54$). Post-study situational interest also did not differ between the robot condition (M = 5.16, SD = 1.22) and the control condition (M = 5.40, SD = 1.22; $t_{22} = 0.50$, $P = 0.62$). We also found no differences between pre- and post-situational interest scores for the robot condition ($t_{11} = 0.92$, $P = 0.38$) or control condition ($t_{11} = 0.54$, $P = 0.59$).

We then conducted two regression analyses to examine usage patterns and found similar reading engagement in both conditions (Fig. 4). The first analysis used the social-robot manipulation condition (i.e., control or robot condition), prior reading interest, and initial situational interest to predict number of days read. The regression model explained 31.9% of the variance ($R^2 = 0.319$, $F_{3,20} = 3.122$, $P = 0.048$) and included two significant predictors of number of days read: prior interest in reading [regression coefficient (β) = 1.85, $P = 0.027$] and initial situational interest (β = −1.65, $P = 0.009$). We also tested all two-way interactions between the variables and found no significant effects. In this model, each one-point increase in prior interest in reading predicts reading for 1.85 additional days, and each one-point increase in initial situational interest predicts reading for 1.65 fewer days. Although the interaction between these two variables is not significant, it appears that low interest in reading coupled with a high initial situational interest had a strong negative effect on reading. It may be that children with a mismatch between high initial situational interest and low prior interest felt that the activities would be exciting and interesting at first but may have then been disappointed by them once they began to engage in reading, which led to lower reading times. However, this relationship requires further investigation.

The second regression model used condition, prior reading interest, situational interest, reading goal, and day of the study to predict reading time for each participant on each full day of the study. The model accounted for 24.41% of variance ($R^2 = 0.2441$, $F_{6,305} = 16.42$, $P < 0.01$). There were three main effect predictors of minutes reading each day: day of the study (β = −0.99, $P = 0.0017$), reading goal (β = 0.48, $P < 0.001$), and initial situational interest (β = −15.32, $P = 0.011$). The interaction between prior reading interest and initial situational interest was also a significant predictor (β = 2.29, $P = 0.028$) and was included in the model. This model suggests that, for every increase of 1 min for their reading goal, children read for an additional 30 s, and for each day of the study, students were likely to reduce their reading time by nearly 1 min. Thus, even while controlling for other factors, reading time was not dependent on whether the child read with the robot or completed the guided reading in the paper-based activities. Rather, reading time was most closely associated with the child's reading goals, prior interest in reading, and their situational interest in the activities at the beginning of the study. A high initial situational interest was a strong negative predictor for reading time, but this effect is mitigated by the positive impact of the interaction between prior reading interest and situational interest in the model. That is, a very high situational interest was only a negative predictor of reading time if the child also had very low prior interest in reading.

In summary, we found that study condition did not have a significant effect on our two measures of reading engagement, number of days read, and average reading time, indicating that children had similar reading engagement with the robot and the paper-based guided reading activities.

Qualitative results

We present the qualitative results reported here in two sections. The first compares the reading experience of children who read with the

A Child reading with the robot **B** Child reading with the paper-based activity

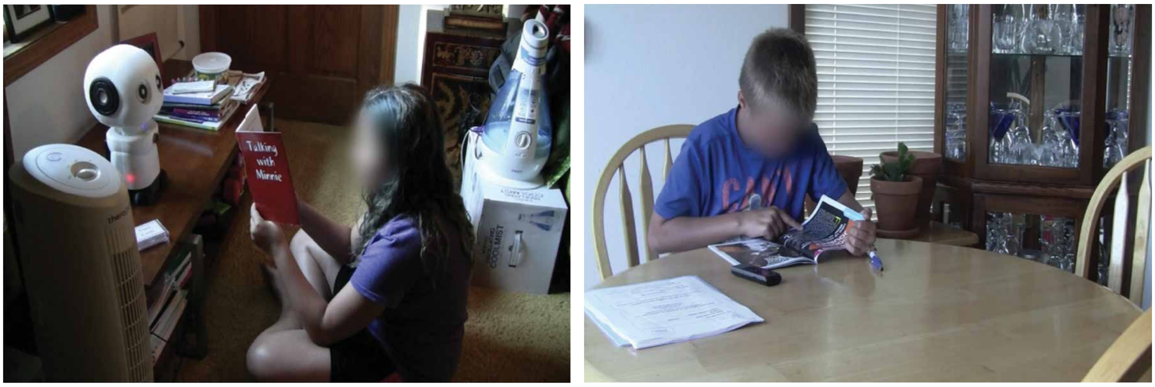

Fig. 5. Children engaging in study reading activities. (**A**) Child reads out loud from the introduction book *Talking with Minnie* to the robot during the first visit. (**B**) Child in the control condition reads out loud into an audio recorder (pictured near book) from the book *LeBron James* while recording his activity in a reading packet (bottom left of picture).

robot (robot condition; see Fig. 5A) with those who completed similar paper-based guided reading activities (control condition; see Fig. 5B). The second presents changes in how children describe their experience with reading with the robot over time. Both analyses focus on codes of pre- and post-interviews. Details of count data and definitions for each of the codes can be found in tables S2 and S3. Figure 6 shows comparisons between groups for select codes from pre- and post-interviews that are relevant for this report. Throughout this report, we used participant IDs (e.g., C111 or R302) to attribute direct quotes to the children who said them.

Comparing conditions

Results from our post-interviews indicated that children found both guided reading activities to be positive, enjoyable, and engaging experiences that help build reading skill. Those in the control condition focused more on the structure, goal setting, and improvements in reading fluency, whereas those in the robot condition discussed improved reading comprehension and increased motivation to read. Figure 6A demonstrates these comparisons.

Control condition. In post-participation interviews, all 12 of the children in the control condition reported a positive experience with the reading activities. They described the activity as "kind of fun" (C188) and stated that they "like it the way it is" (C643). When they were asked what they liked most about the reading activities, many children referred to the act of reading and the books included in the study. They said that they liked the activities, because "to me it just feels like reading, which I like" (C012) and they "really liked the books" (C164). There were two major reasons that children in the control condition appeared to enjoy the reading and the books in the study: They liked the opportunity to improve their reading fluency and the choice of books provided. They felt that the structured reading and reading out loud were opportunities to improve their reading fluency. For example, C783 said, "it helps you become a more [sic] better reader, [because] you're setting a goal every day by reading that many and the books you read [sic]. And by… saying if you've met your goal every day." Some children felt the diverse set of books gave them incentive to read. C054 said, "I liked the books, and some of those books I didn't know about. Then I read about them, and I liked them." Exposing children to books that they had not considered reading before often came up, as C211 explained, "I got to read books that… I have never heard of."

Although their descriptions of the reading activity were positive overall, children in the control condition had a larger number of negative (10) responses to questions about their experience, and few (4) suggested that the activities motivated them to read more. Reading out loud and the structure of the reading activities were cited as ways to improve their reading ability, but children also reported that these were not always enjoyable. For example, when asked about reading, C555 said, "I didn't not like it, but I didn't like, really enjoy it." He was asked to further explain, and he said that he did like most of the activity, but "I don't really like reading out loud." This dislike of reading out loud was a common answer for the 10 children who had negative responses to describe some aspect of the reading activities. Even when they felt that the reading out loud was good for them, some children found it tiring. For example, C012 said, "I just got a lot more tired… sometimes my throat hurt after doing it." Others found that writing in the log and recording their reading were cumbersome, as C701 told us, "It felt like it was like time consuming, because like I would have to flip back to the last [page in the packet] and say, 'oh okay' I did that and do the last time reading for that."

Robot condition. All 12 children in the robot condition also reported a positive experience in their post-participation interviews, although they more readily talked about interacting with the robot. They liked the activity because they "loved" the robot (R302) and it was "fun to read to a robot" (R083) and "a cool experience" (R111). This activity also helped them feel that they were improving their reading comprehension and motivated them to read more than they normally would. Many of their descriptions suggested that Minnie's comments helped them better understand what was happening in the book. R111 echoed a common theme for the eight children who suggested that it improved their reading comprehension when he said that the robot "made me think about what I just read more." Although Minnie's comments were not designed to serve as cognitive aids, the children saw them as "summaries" that helped them understand the text or the words better. R302 said, "I didn't know some of the words and Minnie would like help me with that." They also indicated that reading to the robot encouraged them to spend more time trying to sound out unfamiliar words. R083 said that because, "I know that I am reading to somebody else, I don't like getting judged on things. So, I tried to better to… sound the words out."

Similarly, R316 stated, "you'd have to like make sure what you're saying is correct."

Seven children also seemed to find that reading with the robot also motivated them to read more. Those who found themselves motivated to read more said that the robot "makes me read more" (R389). They felt "more obligated to meet [reading goals] because I had someone who would read with me" (R302) and "when I am reading to myself I really don't want to read at all. But this was fun" (R333). The social connection appears to be, at least in part, responsible for increases in motivation to read, and children were aware of this connection. As R083 suggested, "I would read more, and more people would," because "if someone tells me to go read, to go in the room, I don't have to be alone. There is someone that talks in there."

In contrast to the control condition, fewer children described the reading activities in negative terms (four), focusing on design and technical problems that lessened the overall experience. For example, R333 found the robot's movements to be distracting. She said, Minnie "would move too much and then I would turn around and I would be like, stop." Others also felt scanning cards during the interaction detracted from the experience and suggested that the experience would be better, "If it could be voice activated… instead of having to scan" (R111). There also were several times that technical problems or malfunctions were described as detracting from the reading experience. R599 told us, "the last time I read, I tried to scan it and it didn't scan so that, it can get like I guess kind of frustrating." R842 seemed to have both the largest number of technical issues and was also the most displeased with reading with the robot. He said, "I'd rather just read by myself. It is not really for me. The scanning was annoying… I don't want to have to scan every time I want to do something." Overall, eight children in the robot condition reported some technical issue during the study, including difficulty scanning the tags, incorrectly read tags, and unintended shutdown of the system, whereas only one technical issue, low batteries in the audio recorder, occurred in the control condition.

In sum, the robot appears to have facilitated sustained reading activity equally as well as the paper-based guided reading, because there appears to be little difference in situational interest, positive feelings, or engagement between conditions. Those in the robot condition felt support for reading comprehension and more motivated to read, whereas those in the control condition felt that the activity improved fluency.

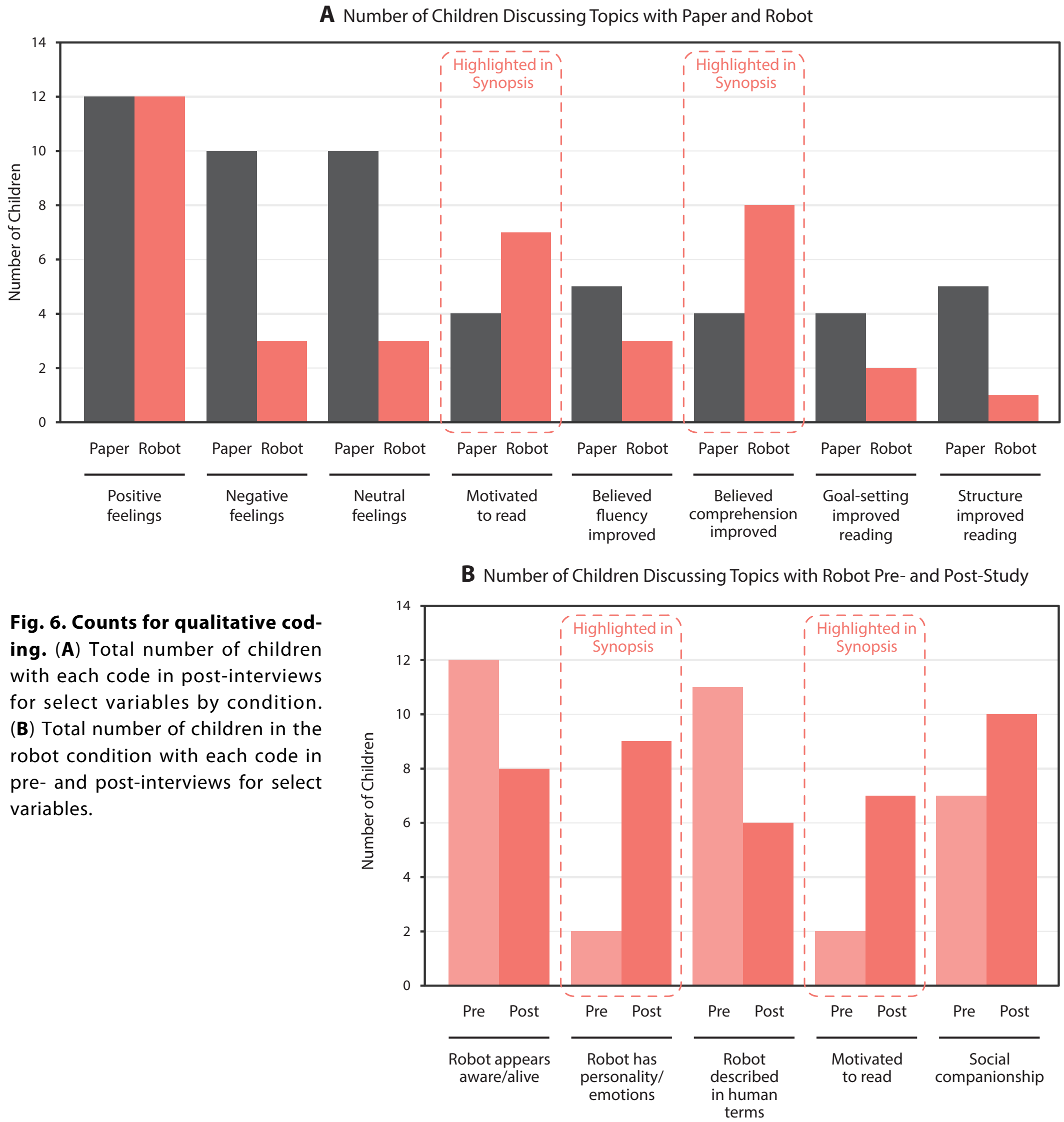

Fig. 6. Counts for qualitative coding. (**A**) Total number of children with each code in post-interviews for select variables by condition. (**B**) Total number of children in the robot condition with each code in pre- and post-interviews for select variables.

Changes in robot reading experience

The most common theme from children who read with Minnie was that their reading was a profoundly social activity. Initially, the children described the robot in terms of its physical capabilities. After 2 weeks, they began to describe the robot in terms of its emotional responses and personality. Figure 6B shows the pre- and post-interview codes for each child in the robot condition.

Pre-participation (initial) experience. Seven of the children initially suggested a strong social companionship to the robot. The robot was described as a "partner you can read with" (R111) that could "talk with me" (R302), as "somebody to talk to" (R083), and as "someone to read to, so you don't feel alone" (R389). The idea that reading was now an activity done with someone else was a strong sentiment in many of our pre-interviews. R599 felt very strongly about the benefit of reading with Minnie. She said that it was "better than reading by myself" and said, with the robot, "I'm not bored." Further, some suggested that the social activity did not include some of the negative aspects of reading with others, such as being interrupted or being judged for making mistakes. R595, who lives with several siblings, said that reading with Minnie was "better than normal reading" and said, "I have someone to read to that doesn't interrupt."

During pre-interviews, 11 children described the human-like features of the robot to explain why they felt they were reading with someone. R599 said Minnie "acts like a person" and "doesn't just like sit there and stare at you." R316 also mentioned the robot's physical movements as reasons to believe that they were reading to someone. They said that the robot's "head doesn't just like sit there… staring at you. So, it kind of gives it a little bit more realism."

Post-participation experience. In the post-participation interviews, more children began to describe Minnie as a social companion and included descriptions of the robot's feelings, emotions, and personality. Ten children now described the reading activities as a social activity with a companion. They said that "she is… friendly" (R083), that they could "talk to her about the book" (R302), and that reading with Minnie was like reading at a "book group meeting" (R111). This description went beyond simply having someone there; nine of the children seemed to have a sense that she had feelings, emotions, and a personality. For example, R389 said that Minnie could "say… what she thinks about [the books]," and R241 felt Minnie "had a lot of emotions about the books… She was scared when I was reading about 'The Magic Treehouse.' If something had happened to Annie and Jack… she was scared and I like that." This sentiment contrasted with the children's experience reading with other people. R599 said, "[Minnie] tells you… what she thinks about it in the story when you scan it. And that… it's not just reading, it's reading with someone" and went on to explain, "I usually read with my mom. But, she doesn't tell me like what she thinks about the story." These emotions were now also included in explaining how the robot motivated them to read. For example, R389 told us, "it made me want to read more because it made you feel like you had to make it happy."

DISCUSSION

We aimed to contribute to the social robotics literature by examining how an in-home learning-companion robot influences the reading experience of children during guided reading activity and how this experience changes over time. As expected, most of the children in the robot condition viewed Minnie as a social companion while reading. This social companionship resulted in a transformation of the reading experience from an isolated, structured activity to a socially situated and collaborative effort. Our results suggest that the in-home reading activities with the robot were sustained, and the feelings of social companionship deepened over time.

Comparing conditions

RQ1 asked how the experience of completing guided reading activities changed when facilitated by a learning-companion robot. Our quantitative measures show that children in both conditions demonstrated and reported high engagement and interest in the guided reading activities. Our qualitative analysis shows that children in the robot condition had fewer negative comments about their activity and that reading with the robot supported self-reported reading comprehension and motivation to read. These observations are consistent with prior work that suggests that socially situated reading promoted shared cognitive activity and contributed to improved comprehension and motivation to read (*5*). Also consistent with prior work, children appeared to find their interactions with Minnie to be a social experience (*36*, *46*). This social reading, specifically Minnie's comments, improved their feelings that they understood the text. In contrast, the control condition was not seen as a social reading experience, and this sentiment of comprehension support was rarely brought up by those in the control condition. Thus, it is likely that the social supports contribute to the feeling of comprehension support. The overall positive response in both conditions shows that the design of the reading activity itself (with or without the robot) was effective for supporting reading practice at home, and we found that the children who read with Minnie further experienced reading as a socially situated and collaborative effort that may benefit reading comprehension and motivation beyond the paper-based activities.

Examining the robot condition experience over time

RQ2 asked how the experience of working with a learning-companion robot for in-home reading changed over time. We found that, over time, situational interest and reading engagement were generally sustained with moderate declines in reading, and an initial sense of social companionship with the robot deepened.

Our quantitative results revealed similar situational interest, for pre- to post-study measures, and a negative effect of time on reading, with a small decrement (about 1 min) of reading time predicted each day. Although there was a measurable reduction in time spent reading over time, both conditions supported reading engagement, given that children in this age group rarely engage in voluntary reading (*16*) and that these children read during their summer break. Because the guided reading activity itself was a successful reading intervention, we believe that the similarity in engagement between the two activities demonstrates the quality of the reading activities, rather than a deficiency of the robot to positively affect reading engagement. In addition, the number of technical issues that occurred may have negatively influenced reading engagement with the robot by the end of the study. Two-thirds of the children in the robot condition reported that some technical aspects of the robot were lacking, some describing these as "frustrating" (R316), which may have dissuaded some of the children from reading more often. This result is consistent with prior work that demonstrates that an overestimation of a robot's capabilities can negatively affect engagement and relationships with the robot (*32*, *33*). We believe that the social support provided by the robot and the deepened connection children had with the robot may have reduced some of the negative effects of the technical problems.

Our comparison of pre- and post-interview data suggests that children continued to find the activity with the robot to be highly social. This social connection transformed in-home reading from an isolated activity into a social one, where the children now had "someone to read with." Consistent with prior work in interest development (*4*, *5*), many children expressed that the social connection with the robot added an additional motivation to read. Children in the robot condition reported feeling that reading with Minnie supported reading comprehension, which is consistent with prior work on the learning benefits of reading socially (*12*, *15*).

Rather than wearing off over time, our qualitative data provide evidence that children's social connection with the robot appeared to deepen. It appears that seeing the robot as an emotional entity that has feelings may require time to develop, but this development might not need a very complex interaction to occur. Minnie is designed for appropriate social interaction but is not equipped with sophisticated nonverbal cues, other than gaze cues to communicate attention and to depict thoughtfulness, or spoken comments to convey emotion and personality during reading. Children often referenced Minnie's comments, designed to be informal and often personal based on recommendations by Leite *et al.* (*9*), when describing the robot's emotions. This style of comment appears to have been perceived by the children as the robot having a personality and emotion. This display of emotion is essential in establishing a deeper and more meaningful social connection between humans (*32*) and between humans and robots (*29*, *33*) and is an indication of a deepening social connection between Minnie and the children.

Summary and limitations

In the coming decades, robots will become increasingly ingrained into several key domains of everyday life, including learning and education. To take advantage of their potential to support learning, we must carefully design social robots to connect and engage with children in ways that meaningfully promote learning and interest in academics. Minnie, a social robot designed with evidence-based design principles, appears capable of making and sustaining important social connections with children and of sustaining, enhancing, and transforming in-home guided reading activities. The robot portrays value for reading, emotion, and feelings while talking about books with children, which deepens the social experience and the child's value for reading. It also models quality reading habits, such as summarizing, predicting, and discussing the readings. These deep social connections coupled with meaningful reading activities transformed the in-home reading experience such that children sustained reading engagement over time, felt that they understood more of what they were reading, and felt that they were sharing this experience with someone who was interested in their efforts. We demonstrate that social robots might be incorporated into learning activities at home to reach their potential as educational and learning supplements for the future.

We expect the design elements included in the development of our social robot to inform other researchers and designers of learning technologies and activities and our findings to contribute to the theoretical understanding of how experience with a social robot can change over time, specifically how an initial social connection with a robot can deepen over time to include beliefs that the robot has feelings, emotions, and a personality.

Although we believe that this study makes a notable contribution to the field, the findings are limited by several factors. First, because of the small sample, we are unable to make strong generalizable claims. Larger sample sizes involving quantitative data are necessary for more conclusive claims. Second, the length of our study may be too short to make measurable differences in interest and behavior. Studies in interest development can rely on months or years to capture changes in interest, and studies of social robots as learning companions must explore such effects on similar time scales. Third, our study is limited in examining children aged 10 to 12 years during their summer break. We chose this age group because social connections with a robot may peak at this age (*25*), but how our results generalize to other age ranges is unknown. Furthermore, children do not have the usual time constraints of school, and interactions during the school year may be different. We are also limited in our ability to interpret the interaction between high initial situational interest and low individual interest. We suggest that future work explore this interaction in more detail to interpret and examine the findings. Finally, time on task served as our measure of reading engagement, and a measure of the quality or efficiency of the reading may better capture the differences between reading with the robot and other materials. Although collecting and analyzing this type of data in a field study are challenging, methodological developments might enable the use of such measurements.

Our findings are also influenced by our choice of reading activities and method of delivery of those activities for our control group. Children in the control condition felt that the structure and goal-setting aspects of the activities were useful tools to develop reading skill, which indicates that the reading activities in the control condition were well received, and the quality of those activities made them a competitive baseline against which to compare. We included a robust control condition to avoid a "straw man" comparison. Comparing the robot against unstructured reading activities might better characterize the full extent of the robot's ability to promote reading engagement.

The technical choices made in designing the robot limited some of its effectiveness "in the wild." The experiences of some participants were diminished by technical challenges inherent to the robotic system, such as errors with misread AprilTags, accidental shutdowns, and simplified interactions with RFID cards and AprilTags. Although these deliberate technical simplifications produced a fairly robust system, enabling extended maintenance-free use in the field, improving the core technology and the interactivity of the social robot platform will offer a more seamless user experience.

In summary, our social robot, Minnie, demonstrates the potential for transforming reading at home from an isolated activity into a social and collaborative experience that can promote comprehension and interest in reading. Our results illuminate how we might maximize the societal benefits of imminent robotic technology and demonstrate how the integration of social robots into an existing human activity can transform human experience toward this good.

MATERIALS AND METHODS

The goal of this study is to examine how an in-home learning-companion social robot influences the reading experience of children during guided reading activity and how this experience changes over time. In this study, early adolescent children ($N = 24$; 10 males, 14 females; ages 10 to 12 years) participated following child assent and parent/guardian informed consent after the nature and possible consequences of the studies were explained, and children were randomly assigned to a robot or control condition. The robot condition used a modified version of the Minnie robot designed in our previous work to facilitate reading activities over the course of 2 weeks. The control condition involved a paper-based reading activity, modeled after the robot-facilitated reading activities, that was designed to be completed as a daily diary-type entry. A sample page from the control condition reading packet is included in fig. S1.

Data collection

During our first visit to the children's homes, children completed a questionnaire, including an individual interest-in-reading scale (prior reading interest), before engaging with the robot; a short interview about their initial impressions (pre-interview); and a situational interest scale (initial situational interest) after reading with the robot or paper-based activity for 15 to 20 min. The robot or paper-based activities were then left with the child for 13 additional days. During this time, the child's reading was audio-recorded either automatically by the robot or via a handheld audio recorder operated by the child. Reading usage logs, including duration, date, what book and pages were read, and whether the reading goal was met, were automatically captured in the robot condition and manually recorded by the children in the control condition. After 13 days, during a follow-up visit, children again completed an interview about their reading experience (post-interview) and a questionnaire including the situational interest scale (post-situational interest). To reduce any potential socially desirable response bias (*48*), before each set of self-reports, we emphasized to children the "importance of telling us the truth about how they feel" and that we needed their "honest opinions to understand how to best design our robot."

All interest scales were based on previously published, validated measures of individual (*49*, *50*) and situational interest (*51*). All interest surveys used seven-point (1 = strongly disagree, 7 = strongly agree) Likert-style items.

The daily reading times were collected from reading usage logs. Our analysis included all reading data from each of the 13 full days that children participated in the study. All reading time data from the first introductory day were considered as part of the acclimation period and excluded to control for novelty effects. We include additional details about audio log data analysis and describe our analysis of the novelty effect in the Supplementary Materials.

All data collection procedures were designed in collaboration with and approved by the University of Wisconsin–Madison Institutional Review Board. All families were made aware of the functionality of the audio recording devices, and steps were taken to reduce the possibility of accidental recording of nonstudy activity.

Statistical analyses

All interviews were video-recorded, transcribed verbatim, and coded using a constructivist grounded theory approach [see the Supplementary Materials for additional details on this methodology (*52*)]. We began with an initial round of open coding to describe the content of each interview. We then conducted a round of focused coding of the initial codes to identify generalized themes within the data. We identified 20 axial codes from focused coding that were applied to the transcripts of each interview (see table S1). Interrater reliability was tested on 10% of the total sample and was high ($\kappa = 0.85$) based on estimates with a Cohen's κ greater than 0.80 as criteria for reliability.

Means for each scale were calculated by averaging the scores from all items on the scale. The prior reading interest scale (M = 5.35, SD = 1.09, $\alpha = 0.86$), initial situational interest scale (M = 5.27, SD = 1.34, $\alpha = 0.95$), and post-situational scale (M = 5.28, SD = 1.15, $\alpha = 0.98$) were all found to be reliable using Cronbach's α greater than 0.80 as criteria.

All statistical tests used an α level of 0.05 for significance testing. Regression models included predictor variables theoretically related to contribute to the outcome measure and involved diagnostic tests, including examination of outlier data points, multicollinearity of variables, homoscedasticity, and normal distribution of residuals.

SUPPLEMENTARY MATERIALS

robotics.sciencemag.org/cgi/content/full/3/21/eaat5999/DC1
Materials and Methods
Table S1. Examples of implementing the robot design elements.
Table S2. Counts of qualitative codes.
Table S3. Qualitative code definitions.
Fig. S1. Sample page from daily reading packet for paper-based control condition.
Data S1. Collected interview transcripts.
Data S2. Survey responses.
Data S3. Summary data.
Analysis Code S1. Science robotics analysis.

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