

Improving Interest and Learning with a Learning Companion Robot and Interest Scaffolding: An
Integrated Learning Sciences, Interest Development and Social Robotics Approach

by

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I leave Sisyphus at the foot of the mountain! One always finds one's burden again. But Sisyphus teaches the higher fidelity that negates the gods and raises rocks. He too concludes that all is well. This universe henceforth without a master seems to him neither sterile nor futile. Each atom of that stone, each mineral flake of that night filled mountain, in itself forms a world. The struggle itself toward the heights is enough to fill a man's heart. One must imagine Sisyphus happy. - Albert Camus

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Abstract

There is an established positive relationship between learning that creates a deep understanding in academic content and the development of interest in that content. Recent advances in learning sciences and interest development research have also emphasized the importance of social supports and interaction and the need for personalization during learning to improve educational outcomes such as the development and maintenance of interest in a content area and knowledge construction in that content. In this dissertation, I suggest that *interest scaffolds*, instruction tailored to meet the specific interest development needs of students, which are delivered by a social companion robot, may be an especially effective educational technology to enhance the learning experiences of children and improve educational outcomes. This paper describes a series of three studies designed to test this claim. The three studies use multiple methods of analysis and include: initial development of interest scaffolding design guidelines and a social robotic platform to facilitate scaffolded activities; an extended field study of the robot during in-home interaction; and a randomized controlled laboratory study comparing learning outcomes during a robot supported learning activity with or without socially adept robot actions. Findings suggest that a social robot using interest scaffolding fundamentally transforms learning tasks that have been traditionally isolated and individual (e.g. homework) into collaborative activities that can positively impact interest development and knowledge construction, and that socially adept behavior by a robot improves children's feelings of social connection with the robot, situational interest, and deep understanding of content.

Introduction

In the last several decades, educational researchers and learning scientists have emphasized that impactful learning should focus on deep conceptual understanding rather than the simple acquisition of facts and procedures, and this type of learning requires focused effort, self-regulation, and perseverance through challenge (Bransford, et al., 2006; Sawyer, 2014). Creating scaffolding to regulate cognitive demands during learning activities has a rich history and is thought of as crucial to developing deep understanding (Puntambekar, & Hübscher, 2005; Sawyer, 2014). Traditionally, *scaffolds* are supports during learning, including working with more knowledgeable others or agents, that are tailored to the specific needs of individual learners to promote active participation in the task and allow the learner to perform tasks normally too complex for them to complete on their own (Wood, Bruner, & Ross, 1976; Resier & Tabak, 2014). Beyond cognitive scaffolding during learning activities, there is a long-established positive relationship between knowledge construction in academic content and the development of interest in that content that is thought to promote deep understanding during learning (Lazowski & Hulleman, 2016; Renninger & Hidi, 2015). Just as learner's needs differ based on their cognitive skills, abilities and conceptual understanding, learners have different needs based on the depth or phase of their personal interest in what they are learning (Renninger & Su, 2012). Thus, we can expand our vision of the scaffolding metaphor to include *interest scaffolds*, scaffolds that provide tailored supports for learners to engage in tasks based on their interest in the content they are learning. To further promote deep understanding during learning by incorporating scaffolding into learning activities, my contention is that providing interest scaffolding is of equal importance to cognitive scaffolding, yet we know far less about how to implement interest scaffolds. Designing learning environments to provide effective interest

scaffolding has the potential to make an incredible impact on students and can be a transformative mechanism for student achievement, because instruction can be adapted to support cognitive processes, as well as interest and engagement for those with lower interest, and also continue to challenge and motivate learners with already high interest (Järvelä & Renninger, 2014).

There is a growing body of research that suggests that there is a crucial role for social interactions in supporting interest development (Bergin, 2016; Pressick-Kilbourn, 2015). That is, much of what researchers prescribe as effective supports for interest development – promoting positive affect, while building value and knowledge for the content (Hidi & Renninger, 2006) – are further enhanced when there are additional social supports during learning activities (Bergin, 2016). Thus, scaffolding for interest would be best served by also providing social supports and interactions that are effective for developing interest. I refer to interest scaffolds that also include socially supportive elements as *socially situated interest scaffolds*. One way to address the need for providing socially situated interest scaffolding, on a large scale, is to design educational technologies – increasingly capable of providing personalized learning activities to students – to include supports, based on current interest and motivation research, that promote interest development in academic content through social interaction. A social robot may be an especially effective educational technology to provide socially situated interest scaffolding during learning in academic content, because of their ability to transform learning activities to include social supports and interactions and to personalize the learning experience based on individual learner needs. This effect may be particularly powerful for learning activities at home, where homework is often done in isolation, that could benefit from social interaction and interest development support. Given the increasing availability of educational robotics (Benitti, 2012; Belpaeme,

2018), it is crucial that their potential for positively impacting interest development, knowledge construction and academic achievement is examined through rigorous study.

The studies included in this dissertation are guided by several aspects of research on interest development and human-robot interaction that are underexplored and require further investigation. One major issue in these fields of research are that much of the current theory in interest development and motivation research is built primarily through case study and correlational investigations (Lazowski & Hulleman, 2016). While this provides several outlets for theoretically prescribed guidelines for interest interventions, there is a severe lack of theoretically grounded intervention studies that assess the efficacy of implementing personalized learning activity supports for interest development, and their subsequent impact on learning outcomes. A second major limitation of prior work is that studying the ability of a robotic agent to *maintain* its social connections over time and in real world settings is also greatly underexplored (Leite, Martinho, & Paiva, 2013). Most current work in human-robot interactions focusing on social robotics examines people working with robots during limited interactions in lab settings, which leaves a need for field-study research over time to observe more realistic interactions. Finally, to my knowledge, there have been no studies to test the effectiveness of a social robot to use interest scaffolding to improve knowledge construction and interest in academic content.

In this dissertation, I address these limitations through a series of three research studies. The overall goals of this work are to support the educational application of socially situated interest scaffolding and social robotics by:

- 1) creating design guidelines for developing a social robot programmed with socially situated interest scaffolded learning activities to promote social connections, lasting interest and knowledge,
- 2) examining how children perceive and interact with the robot during authentic, in-home, long-term situations, and
- 3) empirically testing whether working with a robot designed with socially situated interest scaffolds has a greater effect on understanding, situational interest and social connection-making outcomes when it is programmed with socially adept behaviors compared to a robot with minimal social behaviors.

The studies in this dissertation make theoretical contributions to interest development and learning sciences literatures by validating current theoretical prescriptions from these areas with much needed empirical evidence on the effectiveness of interest scaffolded interventions to improve situational interest and deep understanding that lead to lasting interest and knowledge in a content area. These findings will also contribute to theory in interest development and human-robot interaction by demonstrating whether a robotic agent can be effective in playing the role of a social other in interest development. It also makes an important contribution to human-robot interaction theory by reporting on how children use a social robot in real settings (e.g. the home) for an extend period, their perception of social interactions with the robot, and how their experiences change over time. Finally, this work will provide practical guidance, through design guidelines for socially situated interest scaffolds, for those developing and implementing educational robotic technologies.

Background

To understand how a social robot should be designed to provide socially situated interest scaffolding, I draw on lessons from learning sciences, interest development, and human-computer interaction (HCI) research. Integrating these perspectives allows for a rich cross-pollination of theory where scaffolding designed for an educational robot can use complementary theory from learning sciences and interest development research to inform our understanding of how human-human interactions support both cognitive processes and interest development during learning. For example, engaging in learning activities with a social other benefits deep understanding, as the learner is able to co-construct understanding or comprehension with another learner, and also interest, as the social other may reinforce the learner's emerging identity in relation to the topic they are learning about (Järvelä & Renninger, 2014). This understanding of effective human-human interaction can then be modeled using HCI methods and modified based on HCI theory to design similar supports during human-computer or human-robot interactions. Examining the process of learning and interest development during HCI studies can also inform what we know about *how* people learn and develop interest, particularly in socially situated settings, which can further inform learning and interest theory. In this way, each theoretical perspective compliments one another, informs theory in the other disciplines, and can be triangulated to inform robust practical application. As the opportunity for providing personalized learning activities with social robots increases, research that integrates these multiple perspectives will provide practical aid in informing the design of these robots to maximize the educational and motivational benefits of working with such robots.

Learning Theory

The modern era of education research has focused on developing student content knowledge from a *knowledge construction*, or constructivist, perspective that goes beyond the acquisition of simple facts and procedures to consider knowledge as being built on deep understanding of concepts, integrated within larger cognitive frameworks of information and experiences (NAS, 2018; Sawyer, 2014; Mayer, 2001). Lessons from learning sciences research suggests that to develop deep understanding of academic concepts, learners benefit from supports, or scaffolding, that structure learning activities at an appropriate level of complexity for learners to be successful with, guide their attention to key aspects of learning materials, and aid in organizing and inter-connecting newly acquired knowledge with existing knowledge (Bransford, Derry, Berliner, Hammerness, & Beckett, 2005; van den Broek, 2010). These supports for deep understanding can be provided as scaffolds that can be tailored, adjusted, or removed based on a learner's specific and evolving needs (Puntambekar, & Hübscher, 2005; Vygotsky, 1978). Learners working with more-knowledgeable peers, teachers, or adults can benefit from scaffolding that allows the learner to be given structured support to engage in work they wouldn't otherwise be capable of, or through *modeling*, where the learner observes the more-knowledgeable other as they complete learning activities (Brown, Collins, & Duguid, 1989; Collins & Kapur, 2014). For example, a learner with limited knowledge of computer programming would struggle to write a computer program on their own, but may be able to combine several sub-programs, written by a more-knowledgeable peer or provided as example code, to achieve a meaningful programming goal with the aid of the more-knowledgeable peer (Michaelis & Nathan, 2015a). By including learning scaffolds, learning activities can promote deep understanding of the content as learners actively construct and inter-connect knowledge in

the content, while working at a level of complexity appropriate for their cognitive and social development (Krajcik, et al., 1998; Delen & Krajcik, 2018). Scaffolds can be adjusted or removed altogether as the learner develops new skills, understandings, expertise and abilities, so that they continually work at the edge of their capabilities in order to foster continued knowledge growth (Reiser & Tabak, 2015).

There is also evidence that socially situated learning can support comprehension, problem solving and deep understanding by distributing the cognitive load across the participants in an activity (Hutchins, 1991). Distributed cognition theory suggests that interaction between multiple agents distributes cognitive processes among group members that helps support comprehension, problem solving, making connections across the content being learned and to prior knowledge, and generating new ideas and insights that result from the interaction (Smith, 2008; Hollan, Hutchins, & Kirsh, 2000; Miyake & Kirschner, 2015). Social interaction is effective for improving comprehension when learners collaborate to discuss what they are working on with others. Social others in a group can perform part of the cognitive activity required for comprehension by summarizing and rephrasing their understanding of the material or pointing out key features of a problem, text or representations (Roschelle & Teasley, 1995). Social interactions also promote deep understanding from reading through discussions that prompt new ideas about the content or connect that content to other prior knowledge (Swann & Allington, 2009). People naturally integrate the perspective and problem solving of others when working in social situations (Sebanz, Knoblich & Prinz, 2005), and providing social supports that facilitate coordinated understanding and collaboration can effectively promote knowledge construction (van Joolingen & Zacharia, 2009).

Interest Development

There is also evidence that *interest* is closely related to deep understanding and knowledge building (Hidi & Renninger, 2006, 2015; Harackiewicz, Smith & Priniski, 2016). Researchers studying *interest development* distinguish between *catching* (or triggering) and *holding* (or maintaining) one's *situational interest*, momentary increases in focus and engagement, during an activity (Mitchell, 1993; Hidi & Renninger, 2006). While catching a person's situational interest triggers increased engagement and positive feelings in the moment, properly holding a person's situational interest by promoting positive feelings, value, and knowledge for the content maintains their interest in ways that will lead to sustained engagement over time. Research in this area suggests that repeated activation of *situational interest*, particularly instances of hold (maintained) situational interest, can lead to the development of *individual interest*, a pre-disposition to re-engage with content (Hidi & Renninger, 2006; Hidi & Harackiewicz, 2000). However, interest does not simply develop on its own, rather students need tailored supports for positive affect, value, and knowledge during learning activities to develop interest in an academic domain (Renninger & Su, 2012), and these supports are more deeply impactful in the context of social interaction (Palmer, 2009; Bergin, 2016). These social interactions give the learner ways to build relationships and share values in common with others who engage in the practice (Basu & Calabrese-Barton, 2007) and feel a sense of social involvement (Palmer, 2009) that support feelings of connectedness (Pressick-Kilbourn, 2015) and belongingness (Bergin, 2016) in relation to the academic content. Positive affect, supported by social and environmental features, can be an important early vehicle for catch situational interest, but it is crucial that an individual also develop knowledge and value for the content to hold situational interest in ways that will induce the desire and capacity in an individual to begin

seeking engagement with content on their own (Hidi & Renninger, 2006; Renninger & Su, 2012).

To provide learning environments that promote the development of individual interest, researchers suggest allowing students autonomy and choice during learning (Deci & Ryan, 1985; Ryan & Deci, 2017), presenting learning activities in ways that are personally relevant (Järvelä, & Renninger, 2014) and appropriately challenging (Nieswandt & Horowitz, 2015), and that are situated within the personal and cultural context of the individual (Bergin, 2016). Research has found that having choice in learning tasks, even involving small aspects, can promote engagement, deep understanding and intrinsic motivation (Patall, Cooper, & Wynn, 2010), and finding personal relevance for the content (Azevedo, 2006; Pressick-Kilbourn, 2015). However, students with low knowledge and interest in the content may need some support in making choices (Katz & Assor, 2007). Choices should be provided that might relate to the student's other interests, and students should be given ample time to explore the content to make personal hooks into what they are learning (Azevedo, 2015). Students can also develop personal relevance through directly suggested (Gaspard et al., 2015; Durik, Hulleman, Harackiewicz, 2015), or self-generated connection making (Hulleman, & Harackiewicz, 2009). Maintaining the appropriate level of difficulty of a learning task to support interest development requires careful adaptation of the content to the ability and interest level of the student. Students with high interest or prior-knowledge need less support for difficult material and can persevere through the challenge (Renninger & Su, 2012), but low interest students may lack the perseverance and self-regulation it takes to overcome even moderate obstacles without support (Sansone, Thoman, & Fraughton, 2015).

To further support interest development through social interaction, a social other should share the experience and excitement for the work, provide access to additional information, and provide guidance with ideas about how and what to pursue next (Bergin, 2016). Bobbitt Nolen (2007) found a social reading environment, where the children engaged in partner readings, shared recommended books with each other, and teachers emphasized the “social value of reading,” promoted developing individual interest in reading over time. Social supports that aid learners in finding content to be valuable and rewarding have also been used to promote interest in science using positive social influence. Jackson et al. (2018) found that, for women, positive social recognition, such as encouraging and understanding the person’s interest in science, is related to increased career interest in science fields. Even simple encouragement can serve as an effective social support; Hulleman et al. 2017 found that the more parents talked to their children about the importance of STEM, the more STEM classes students took in high school. Furthermore, friendliness, humor, enthusiasm and being approachable are all social traits found to support interest through promoting relatedness and belongingness to the material (Linnenbrink-Garcia, Patall, and Messersmith, 2013). Overall, social connections appear to aid an individual in internalizing values for the content, and this process may happen through finding shared purpose, focus, and values with the social others we connect with (Deci & Ryan, 1991).

Human-Computer Interaction

Human-computer interaction (HCI) research has found that humans respond to computers and technology in a social way, and that robots can be designed in ways to elicit a strong social response (Duffy, 2003). In general, working with a computerized agent has been found to enhance the process of learning and knowledge construction more than working without one (Schroeder, Adesope & Gilbert, 2013). These effects are greater with the use of conversational

and polite speech, and human-like actions by the agent (Johnson & Lester, 2016; Kory Westlund et al., 2017). These agents are most often designed as a digital companion, but a robotic learning companion may be best suited to provide social support due to their capacity for greater social connection-making than other technologies (Bainbridge, Hart, Kim, & Scassellati, 2010; Kiesler, Powers, Fussell, & Torrey, 2008; Kennedy, Baxter & Belpaeme, 2014). In general, robots are perceived as friendlier (Han, Jo, Park, & Kim, 2005), and more appealing, perceptive and helpful (Wainer, Feil-Seifer, Shell, & Mataric, 2007) than digital agents, and the social connection with robots appears to peak between ages 10 and 12 (Kahn et al., 2012). So, while the cost of a robotic platform is greater than that of other digital agents, it is believed that the physically embodied nature of social robots has a significant positive effect on the perception of social interactions with a robot (Wainer, Feil-Seifer, Shell, & Mataric, 2006; Belpaeme, 2018). Thus, the benefit of greater social connections may outweigh the additional costs since the more meaningful social interactions would better promote situational interest and deep understanding that in turn build lasting individual interest and knowledge in academic content.

There are several researchers who have studied specific design elements for maximizing the social aptitude of a robotic agent. From a hardware design viewpoint, robots need only basic human-like physical features (e.g. eyes and mouth) on an animated head to elicit a social reaction from children (Martini, Murtza, & Wiese, 2015). The use of eye gaze, including eye contact (Mutlu, Kanda, Forlizzi, Hodgins, & Ishiguro, 2012), and well-timed gaze-aversion patterns (Andrist, Tan, Gleicher, & Mutlu, 2014) can improve recall, feelings of favorability towards the robot, and make a robot appear more thoughtful. Social connections can be established and strengthened by addressing the person by name during interaction or acknowledging what happened in prior interaction (e.g. recalling who won or lost a previous game; Leite, Martinho,

Pereira, & Paiva, 2009), and making individualized recommendations for that person (Lim, Hong, Lee, Suh & Beetz, 2013). Leite, Martinho, and Paiva (2013) synthesize social robotics design research and suggest that social robots designed for *long-term* use should be capable of identifying users, recalling previous interactions, personalizing interactions based on the user and prior interactions, and incrementally disclosing personal characteristics and demonstrating novel behavior. Implementing these findings into the design of a learning companion robot can aid in making a social connection between the robot and a learner that can benefit learning outcomes (Saerbeck, Schut, Bartneck, & Janse, 2010).

Social Reading

One educational application that a social robot may be especially useful for is providing social interactions during in-home reading to support and develop *reading and literacy skills*. Reading at home is an important part of developing reading and literacy skills such as fluency and comprehension (Anderson, Wilson & Fielding, 1988), and reading practice benefits from socially situated learning supports (Guthrie & Klauda, 2014), yet reading practice is often confined to isolated activity. Reading socially can transform the experience into a collaborative activity that provides shared knowledge construction that aids reading comprehension—the process of extracting and constructing meaning from text (Snow & Sweet, 2003)—by both distributing cognitive processes among group members and generating connection-making and new ideas that result from the social interaction (Hollan, Hutchins, & Kirsh, 2000). Thus, children can experience improved reading comprehension 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 with the social other. Children can also benefit from a social other that *models* effective reading habits such as making

predictions and integrating prior knowledge with what they read and processing or summarizing text during short breaks in reading (Palinscar & Brown, 1984; Pressley & Afferbach, 1995).

Modeling that occurs during social reading can be done by demonstrating and reinforcing these effective habits that support reading comprehension (Duke & Pearson, 2002). Since it is important that the reader engage intellectually with text, rather than skimming and attending to surface level content, in order to achieve deep understanding (Goldman et al., 2016), the reader may also benefit from reading with a social other that guides them to think more deeply and engage in reasoning about what they are reading.

Unfortunately, by middle school, attitudes towards reading decline (McKenna, Kear, & Ellsworth, 1995; Sainsbury & Schagen, 2004), and few children voluntarily choose to practice reading outside of school (McKool, 2007). To combat this degrading interest in reading, social reading supports may improve the development of lasting individual interest in reading (Bergin, 2016; Guthrie & Klauda, 2014; Järvelä & Renninger, 2014). The social supports can give the child ways to build relationships, share values in common with others who engage in the practice (Basu & Calabrese Barton, 2007), and feel a sense of social involvement (Palmer, 2009). 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 reading and that reading is important to them (Sansone & Thoman, 2005; Guthrie, Klauda, & Ho, 2013). These supports help develop children's interest, because they gain knowledge and skill in reading and begin to value reading themselves through a natural inclination towards internalizing the values and beliefs of social others (Deci & Ryan, 2000). Providing a social robot as a learning companion for children to augment in-home reading activity, can capitalize on the benefits of socially supported learning to

promote knowledge and individual interest that are lacking during otherwise isolated learning activities.

Social Robots in Education

Robots used in educational applications have been traditionally confined to use as learning tools for science, computer programming and robotics in the classroom (Benitti, 2012), but there has been a great influx of research on robots as tutors or learning companions in the last decade (Belpaeme et al., 2018). Prior work where social robots were used as pedagogical agents has found that learning with robots can: improve basic skills such as vocabulary and language learning (Kim, 2013; Lim, Hong, Lee, Suh & Beetz, 2013; Saerbeck, Schut, Bartneck & Janse, 2010; Tanaka & Matsuzoe, 2012), handwriting (Hood, Lemaignan & Dillenbourg, 2015) and test taking (Brown, Kerwin & Howard, 2013); or make learning more enjoyable (Kanda, Shimada & Koizumi, 2012) and positively influence a child's curiosity (Gordon, Breazeal & Engel, 2015). Studies show that children prefer working with a social robot over a workbook (Liles, Bryant & Beer, 2017) and in a science learning environment, children that routinely asked science questions of a social robot in their classroom had increased levels of curiosity for science (Shiomi, Kanda, Howley, Hayashi & Hagita, 2015).

There are also findings that suggest specific design elements of educational social robots can influence motivational and learning outcomes. Empathic responses to learner activities are found to promote interest and self-efficacy (Kim, Baylor, & Shen, 2007), and foster meaningful discussions (Alves-Oliveira, Sequeira, Melo, Castellano & Paiva, 2018). There are also mixed effects of the robot's competency in the content, where working with a robot designed as a less-able peer can support a learner's self-efficacy but a robot designed as a more-able peer promotes understanding (Kim & Baylor, 2006). A promising study by Saerbeck et al. (2010) found that a

robot programmed with socially supportive behaviors, when compared to a socially neutral robot, improved understanding and motivation in a language learning task. Similarly, Kory Westlund et al. (2017) found that a robot using expressive speech was more effective than flat speech, when the robot read stories and asked children questions about the stories, for promoting vocabulary knowledge as well as concentration and engagement. In math learning activities, dynamic vocalizations from a robot improve rapport and social presence but did not improve any gains in understanding, (Lubold, Walker & Pon-Berry, 2016). While studies have shown that socially supportive behavior by a robot is beneficial to understanding and motivation in some areas, little work has been done to examine the use of a social robot to facilitate understanding and motivation related to reading at home, learning science content, or reading non-fiction textbook materials.

Summary of Dissertation Research Studies

To address this gap in the literature, the research studies in this dissertation present three progressive studies of middle school students working with “Minnie”, a learning companion robot, designed to augment reading activities (see Figure 1 for initial robot design). Minnie’s essential function is to utilize socially situated interest scaffolding to make social connections with children that support knowledge and lasting individual interest. There are nine research derived design elements that form the basis of this scaffolding for Minnie’s interactions with children. The robot: 1) makes tailored suggestions for learning materials, 2) based on student ability and interest; 3) allows children to make choices in their learning tasks; 4) sets, adapts, and monitors reading goals; 5) acts as a partner and 6) demonstrates interest in the activity; 7) uses appropriate non-verbal actions including eye-gaze patterns and face-tracking; 8) references

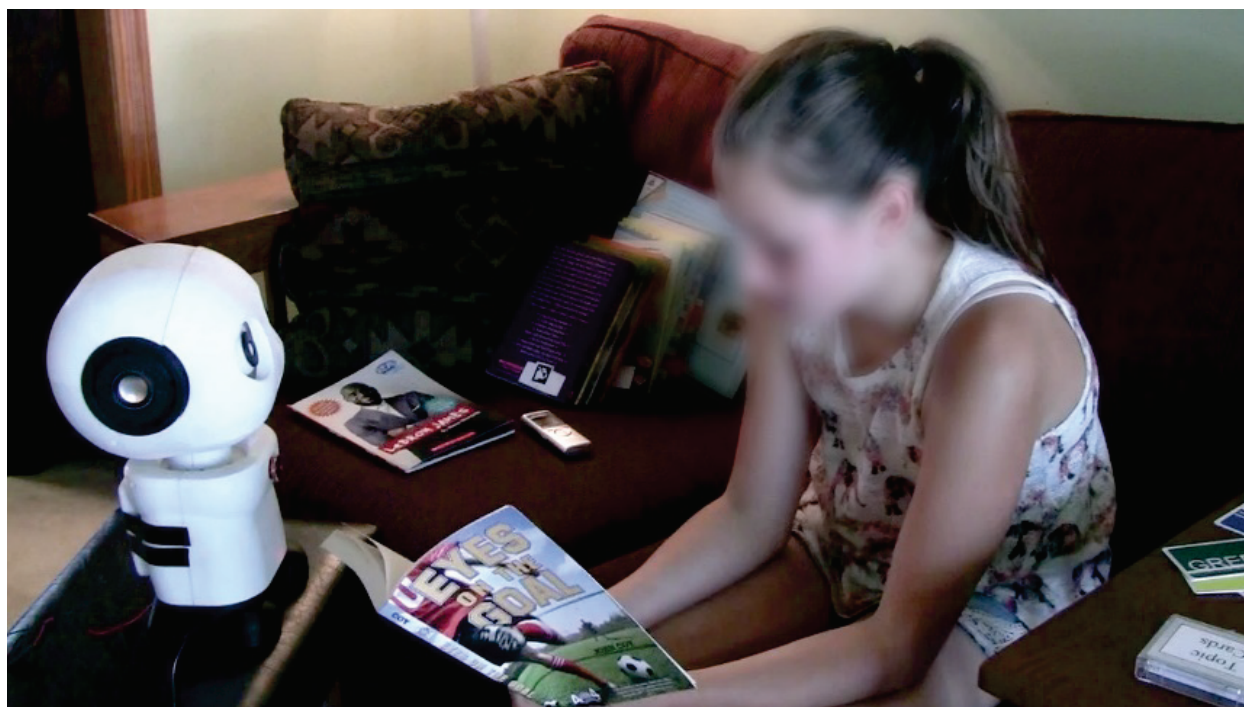


Figure 1. A participant in Study 1 reads *Eyes on the Goal* to Minnie 1.0, the learning companion robot designed to investigate how an interactive robot might support interest development in reading. Books augmented with AprilTags are arranged on the couch to the right of the participant, and Topic Cards and RFID cards can be seen to the participant's left on the arm of the couch.

ID	Design guideline	Source of evidence
DE1	Providing students with autonomy in activities and choosing educational materials	Jones & Brown, 2011
DE2	Setting and monitoring reading goals	Cabral-Marquez, 2015
DE3	Providing materials that align with student topic interests and ability, and supports skill development	Ainley, Hidi, & Berndorff, 2002
DE4	Providing a social partner that demonstrates interest in the reading activity	Sansone & Thoman, 2005
DE5	Reading out loud to a social partner	Rasinski, 2003
DE6	Having the robot maintain eye contact when speaking and averting its gaze while it is "thinking"	Mutlu, 2011; Andrist et al., 2014
DE7	Providing tailored recommendations for content	Lim et al., 2013
DE8	Making references to previous interactions	Leite et al., 2009
DE9	Incorporating personal information, feelings, and beliefs into dialogue over time	Kanda, 2007

Figure 2. Design guidelines for social robot interactions while reading with children to promote interest in reading activities.

previous interactions; and 9) reveals emotions, beliefs and a personal backstory through dialogue over time (See Figure 2).

During interactions, Minnie blinks, makes idle head and eye movements, and uses facial recognition to track the reader during interaction. As students read from books or other learning materials, they can scan id tags, called AprilTags¹, placed in the text, and Minnie will respond verbally with a comment written to specifically correspond to what the child is reading or working on. For example: while a child is reading a book about micro-life in soil, in response to one of the tags on a page in the book, Minnie says, “Now I know why my old strawberries in the fridge are all covered in mold!” Minnie also responds to other basic commands (e.g. answering ‘yes’ or ‘no’) through RFID input (in the initial design of the robot, Minnie 1.0 and 1.1) or touch screen input (in an updated design of the robot, Minnie 2.0). More detail on the initial development of the robotic platform are provided in Study 1 below, as well as modifications made to the system in Study 2 and Study 3.

The learning companion robot was designed as a tool to support reading at home for children aged 10-12, and the series of studies in this dissertation examine how children respond to the robot, how interacting with the robot changes over time, and whether the social robot demonstrates advantages over a similar robot (without socially adept behaviors) for understanding and situational interest. Each of the three studies included in this dissertation have been previously published in peer-reviewed journals or conference proceedings and are presented in a modified form of the published manuscripts. The reporting on the initial development of the robot appears in Study 1 of this report, previously published as a conference paper at the 2017 ACM CHI Conference (Michaelis & Mutlu, 2017). Study 2, previously

¹ AprilTags: <http://april.eecs.umich.edu/wiki/AprilTags>

published as a journal article in *Science Robotics* (Michaelis & Mutlu, 2018), examines the long-term use of the robot and compares that experience with a similar paper-based reading program. In Study 3, I test whether the socially adept behaviors of the robot – characterized by design elements 5-9 above: acting as a partner, demonstrating interest in the activity, using socially appropriate non-verbal actions, referencing previous interactions, and incorporating emotions, beliefs and a personal backstory – have a positive impact on a child’s social perception of the robot, situational interest, and understanding. Study 3 was preregistered² and will be published as part of the 2019 ACM Interaction Design for Children Conference (Michaelis & Mutlu, 2019). What follows are each of the three publications, with some modifications to remove redundancy and provide consistent formatting. I then conclude with a brief general discussion of the overall impact and implications of the three studies, general limitations and proposed future work, and the theoretical and methodological considerations for this cross-disciplinary line of inquiry.

Study 1: Design and Experience Reading In-Home with a Learning Companion Robot

The goals of the work in this study are to explore how young readers currently engage in reading at home and how they imagine technologies such as robots could enhance this activity; to observe how they interact with a robot designed as an in-home learning companion for reading; and to explore their beliefs about how they might use and benefit from a robot as a learning companion. To pursue these goals, I developed an in-home learning companion robot, named “Minnie,” to use as a technology probe.

In the following sections, I report on the use of Minnie, a robot designed with guidelines derived from prior research in interest development and human-robot interaction, as a technology

² <https://aspredicted.org/blind.php?x=ub7de5>

probe to gain a better understanding of how a learning companion robot may be used in a child's home and how the design features of the robot will be perceived by the child and their family. First, I describe how the robot was developed and used as a technology probe for this study. I then detail the data collection method and results, discuss the implications of these results, and finally conclude with theoretical and practical contributions to both interest development and human-robot interaction.

Designing Minnie: A Learning Companion Robot

For this study, I first developed a learning companion robot, Minnie, based on the design guidelines discussed in the introduction to this dissertation. Following design research practices from prior work, such as work by Odom et al. (2012), I then conducted short in-home visits with families to use the learning companion robot as a *technology probe* for discussion and reflection on how a reading technology might impact current reading habits in each home. Hutchinson et al. (2003) describe the technology probe approach as a method with three goals—understanding the user's needs and feelings about the technology, field-testing a technology, and reflection on new possibilities for the technology—that reflect my aims for this study. At this stage of development, prior understanding of the intended user may not be sufficient, which may limit a view of what the learning companion robot should do and how. The introduction of the learning companion into the home may uncover unknown user needs and expectations as well as inspire new thoughts on and possibilities for the learning companion's use. I intend to explore these ideas to inform design modifications to the learning companion robot prior to empirical testing. Thus, the field testing of the robot is conducted concurrent to deep exploration of the design space through the eyes of the user. In short, I study the user, the technology, and their interaction all at the same time.

Each in-home visit began by asking one child (referred to as the *main child*) to complete a short survey on individual interest in reading, followed by an interview (pre-) with the family. After the pre-interview, the researcher introduced the learning companion robot to the family and asked the main child in the home to interact with it for a short period of time (approximately 30 minutes). Following the interaction, the family completed a second interview (post-). In the spirit of using the technology as a probe, the discussion or interaction with the robot were not limited to any preconceived ideas about how, when and where the learning companion should and would be used. Rather, families were allowed to explore ideas about how they would like to or would use this or another technology for reading. The following paragraphs describe this data collection method and subsequent analysis in more detail.

Development of the Robot Platform

The initial design of the learning companion robot was guided by a desire to leverage the power of social interaction to promote interest and engagement in reading. Based on prior work, a small, desktop humanoid robot with multiple methods of interaction and capacity for non-verbal expression seemed appropriate for interaction with a child over the activity of reading. The initial design also planned for the robot to be built on a simple, modifiable, and inexpensive platform in order to model the type of constraints inherent in an affordable commercially available robot. This intuition led to creating the robot using a modified version of a freely available 3D-printable robot design from Hello Robo³ called Maki. A more expensive pre-made robot such as the popular Nao platform by SoftBank Robotics,⁴ while possibly offering a more reliable and polished experience, is not flexible in its physical and hardware design, and the cost

³ Hello Robo: <http://www.hello-robo.com/>

⁴ SoftBank Robotics: <https://www.ald.softbankrobotics.com/en>

would preclude many families from actual use in their homes. The original robot from Hello Robo stands 13.5 inches and has a static torso without any movable appendages (see Figure 3).

The head and neck of the robot contain five servo-controlled motions, including two closing eyelids, a pair of eyes that move laterally together, and vertical and horizontal head movements. These motion options allowed for specific robot behaviors to provide a life-like feel (e.g., blinking eyes) and non-verbal communication (e.g., looking directly at the child).



Figure 3. Image of the learning companion robot, Minnie, used in the study as well as the introductory “Talking with Minnie” book, RFID topic and interaction cards, and books augmented with AR tags. The robot’s camera is the red circle on the upper torso. The RFID reader is below the camera and indicated by a red light when the robot is on.

To perform the necessary computation and facilitate human-robot communication, modifications were made to the original robot design by Hello Robo by adding four pieces of hardware to the robot. First, a Raspberry Pi 2 Model B⁵ microcomputer running the Debian 7 operating system⁶ was added to perform the sensing, actuation, and computation necessary for

⁵ Raspberry Pi: <https://www.raspberrypi.org/>

⁶ Debian: <https://www.debian.org>

the robot's functioning and interaction with the child. Integration of the microcomputer also required modification to the 3D model of the robot that extended the back wall of the robot's torso in the shape of a small "backpack" that would house the computer and provide researchers or end users with easy access to the hardware. Second, a speaker was embedded in each of the ear pieces to allow the robot to utilize text-to-speech responses to the child. Third, an RFID reader was added to the lower front of the robot to allow the child to respond to the robot with four color coded, pre-programmed RFID cards. Roughly, the cards allowed the child to *say* "yes/continue," "no/stop," "pause," and "repeat" to the robot. Fourth, a USB camera was added to achieve two purposes: allowing video input to process facial recognition, which was used for facial tracking, and reading visual tags, AprilTags, placed within books. Each time an RFID card or an AprilTag is scanned, Minnie blinks and makes a distinct beep to let the child know that the scan was registered. The robot platform design afforded implementing the eight design elements identified from the literature review for this study.

Interaction Design of the Robot

The interaction design of the technology probe utilizes the eight guidelines, identified from research in interest development and human-robot interaction to support student engagement and interest in reading, in the following design elements (DE):

DE1: Providing students with autonomy in choosing educational materials;

DE2: Setting and monitoring reading goals;

DE3: Providing materials that align with student topic interests and with which students believe they have the ability to be successful;

DE4: Providing a social partner that demonstrates interest in the reading activity;

DE5: Reading out loud to a social partner;

DE6: Having the robot maintain eye contact when speaking and averting its gaze while it is “thinking”;

DE7: Providing tailored recommendations for content;

DE8: Making references to previous interactions.

Design of the Interaction Flow

During the interaction, Minnie, the learning companion robot, uses facial recognition to track the child’s position and turn its head and eyes toward the child to establish eye contact (DE6). However, to prevent long durations of eye contact from eliciting discomfort, the robot makes idle head and eye movements and engages in gaze aversion. The robot also continually uses pre-scripted dialog based on an interaction flow, described below, which was developed through iterative design and testing.

Introduction. The interaction flow begins with Minnie saying “hello” to the child and providing a brief backstory on why the robot is there (i.e., the robot tells the child that she is a reading coach in training). The child is then instructed to scan and read a book, “Talking with Minnie,” written for this study to acclimate the child to interacting with the robot. This book is written as a story, but the content guides the child through the use of each interactive tool (e.g., how to scan the RFID cards and AprilTags, as well as what they mean) and how to work with Minnie (e.g., read out loud and scan AprilTags). The robot then asks the child to complete a topic-sort activity using 10 topic interest cards (e.g., mystery, art, science, and/or sci-fi/fantasy) labeled with AprilTags. For this activity, Minnie instructs the child to scan all the topics they like followed by any topics they do not like. The robot stores these preferences in the user profile for the child and later uses this as part of a book suggestion algorithm. Figure 4 illustrates a child working during the introduction process.



Figure 4. Image of a child working with Minnie during the introductory process. The child is holding a topic interest card and has placed the “Talking with Minnie” book on the floor in front of Minnie. The books available for the child to read appear on the right of the image. An example of a green RFID card (top) and a topic interest card with an April tag (bottom) are superimposed on the right of the figure.

Goal setting. After completing the initial introduction phase, Minnie begins the process of setting reading goals and selecting books. During this process, Minnie informs the child of a goal for reading time that day (*DE2*)—for this study, the goal was standardized at 20 minutes in length—before each reading session, and begins tracking the time spent reading after a book is chosen. The learning companion robot will then check the user profile for a current book (i.e., a previously read book that has not been finished), and if one exists, Minnie will remind the child of what they were last reading and the page number they were on (*DE8*). The child has the option to continue or not. If no current book is found, Minnie suggests three books (from a set of the 16 available) to the child that they may like.

The robot’s suggestions for books are based on a selection method that uses the child’s reading ability, interest in reading, usual daily reading time, and topic interests to recommend books to the child (*DE3*). Books are first filtered by reading difficulty to include books at an appropriate reading and interest level (*DE3*). To define this filter, the selection algorithm begins

with the child's Lexile⁷ score, a system of estimated reading ability levels for children and matching difficulty levels for books (scale range: 0 – 2000), modify this score for children with high (+100) or low (–100) interest in reading, and define an ideal difficulty range as the modified Lexile score ± 100 . The filter selects books in the available library that falls in this range. These books are then further filtered based on page length by multiplying the child's average daily reading time by five to estimate the length of a book they might complete in a week and selecting books that are ± 20 pages of this value. Finally, the program assigns each book listed in the library a topic match score. To calculate this score, each book is assigned up to five topic labels by a researcher. Points are added to the book's topic match score for any topic that was indicated as a "like" by the user, and points are subtracted for each "disliked" topic. A priority cue is made using the filtered books by placing the highest scoring book at the front of the cue. The top three books in the priority cue are offered to the child as suggested titles (DE7). The child may choose any book they wish (DE1) and scan the AprilTag placed on the back of the book they choose to indicate their selection. The robot then updates the user profile to store the selected book as the child's current book; the robot confirms the title of the book with the child; and the child is asked to begin reading on page one, which marks the beginning of the reading phase.

Reading. In the reading phase, the child is asked to read *out-loud* to Minnie (DE5). Minnie is designed to make semi-randomized movements during the reading phase, which include blinking, moving its eyes, and small turns of its head in order to appear engaged in the reading (DE4). As the child reads, AprilTags will appear roughly every three to six pages of each book, and the child is instructed to scan these tags when they encounter them. The tag ID is

⁷ Lexile: <http://www.lexile.com>

linked to a specific comment, written by the research team, related to what is currently happening in the book (*DE4*). When a scan is received by Minnie, it blinks, makes a distinct *beep*, and delivers the comment via text-to-speech. Each time a book tag is scanned, the user profile is updated to store that page as the current page. During the reading phase, the child may continue to read, scan the *yellow* RFID to pause reading, or scan the *red* RFID to quit reading. This phase continues until the child chooses to quit or scans the last page of the book. At that point, Minnie enters the “end reading” phase.

End reading. The end of the reading phase is triggered by either the child choosing to quit reading or when a book has been completed. In both cases, Minnie will compare the time spent reading to the reading goal previously set (*DE2*). If the child has met the reading goal for the day, Minnie will congratulate the child and begin the shut-down process. Shutting down consists of thanking the child for the time spent reading, encouraging them to read more the next day, and telling the child that the learning companion robot is going to sleep. If the reading goal has not been met, the robot will let the child know how much time is remaining to reach the goal and ask whether they should continue reading. If the child chooses to continue reading, Minnie asks if the child would like to read the same book or a new one and then re-enters the reading phase. Otherwise, Minnie initiates the shut-down procedure.

Shut-down. When a child scans the last page of a book, Minnie will ask the child whether they liked the book, and the child can respond with *yes* (green card), *no* (red card), or *a little* (yellow card). This response is stored in the user profile and is used to trigger a recalculation of book topic match scores. For books the child liked, the topics associated with that book will be given a higher score rating, which will move books with similar topics up the priority cue. The opposite is true for books that the child dislikes. The reading time for the

session is also recorded in the user profile and is used to recalculate the reading goal for the next day. In this way, Minnie takes the child's feedback about the books they've read together into consideration for future book recommendations and personalizes the experience based on their activity (*DE7, DE8*).

By addressing the eight design features identified from previous work, the interaction with the robot may be capable of promoting interest in reading. I next discuss specific methods of interaction that were utilized in this study.

Method

Technology probe study. Several methodological choices were made in order to best utilize the learning companion robot as a technology probe during a brief in-home visit. These choices involved strategically choosing the place of the interaction, engaging the parent(s) and the child in the process of setting up the probe, and interrupting the child during their reading in order to facilitate further exploration of Minnie's features. Researchers also asked the child to behave as if the researcher were not present during the interaction in order to facilitate as authentic an interaction as possible. The researcher intervened only when technical difficulties posed a barrier to their ability to proceed.

The placement of the robot was chosen after the family was introduced to the learning companion robot. The child was asked where in their home they would likely read with the robot. Of the suggestions made by the child, the researcher asked the parent(s) which of these areas they would be most comfortable with conducting the robot interaction and chose to work there. This process helped establish a more authentic interaction between the child and the robot while maintaining the comfort and trust of the parent(s).

The previous section outlined the general interaction design of the learning companion robot. However, in the context of its use as a technology probe, it was unlikely that the child would encounter many of its features due to the short duration of the interaction. To address this limitation, each child was interrupted after approximately 10 minutes of reading and told that they should pretend they were tired of reading the current book. The child scanned the red card to quit reading that book and were instructed to follow Minnie's prompts. Since the reading goal would not have been met, Minnie would tell the child that they had not met their goal and offer to continue reading. Each child was instructed to choose another book and continue reading. Each child could read for a maximum of 40 minutes before being asked to end their reading session.

Participants. The research team recruited families ($N = 8$) from the greater Madison, Wisconsin area to participate in the study through flyers posted around coffee shops, grocery stores, and community centers and through word of mouth. Most often one parent and one child participated, one family included two parents, and one younger sibling was present with two families. For each family, one main child (mean age = 11.6; age range: 11–12; male = 5, female = 3) was asked to interact directly with the learning companion robot. All other family members were included in pre- and post-interviews. All parents involved in the study were asked to review and sign a consent form, and the children were asked to read and express their agreement with an assent form as a part of the study protocol reviewed and approved by the Institutional Review Board (IRB).

Data sources. During the study, I collected data from three major sources. The first data sources were two separate surveys. One survey was completed by parents as a pre-visit questionnaire on their child's reading ability and habits. The other was the Four-phase Interest

Development Reading Scale (FID-RS; see Appendix Table A1), a 10-item individual interest in reading survey, completed by the child prior to working with the learning companion robot. The reliability of the individual interest scale was measured using Cronbach's alpha, with an alpha value of 0.7 or greater indicating, by convention, a reasonably reliable construct (Crocker & Algina, 2009). The second data source was from transcriptions of video-recorded semi-structured interviews conducted before (pre-) and after (post-) the robot interaction. Both interviews were approximately 20 minutes in length, with the post-interview ($M = 19.9$ minutes, $SD = 2.1$ minutes) being slightly longer than the pre-interview ($M = 18.7$ minutes, $SD = 2.3$ minutes). Finally, the third data source comes from coding segments of video recordings made during the robot interaction of about 30–40 minutes ($M = 37.11$ minutes, $SD = 3.18$ minutes). The following paragraphs discuss each data source in more detail.

Surveys. Prior to the in-home visit, one parent from each family was asked to complete a questionnaire to collect information about the main child. The parent was asked to describe, to the best of their knowledge, their child's reading ability, the amount of time their child spends reading non-school work each week, their (the parent's) satisfaction with the amount of time their child spends reading, as well as basic demographic information, such as age and grade.

During the in-home visit, the main child was asked to complete the FID-RS survey to assess the child's individual interest in reading prior to their interaction with the learning companion robot. This survey was developed by rewording items from a previous individual interest survey, developed in previous work (Michaelis & Nathan, 2015b), with language from the reading motivation section of the Motivation for Reading Questionnaire, developed by Wigfield and Guthrie (1997). The survey is comprised of Likert-style items, which asked students to rate their level of agreement with statements using a scale from 1 (*strongly disagree*)

to 7 (*strongly agree*). Scores were calculated by averaging the scores from all items ($M = 5.8$, $SD = 0.82$). The high Cronbach's alpha ($\alpha = 0.81$) indicates it has a high internal reliability.

Interviews and robot interaction. Two sources of video data were captured by the research team: two interviews with the family (pre- and post-) and the main child's interaction with the robot. For the semi-structured interviews, a pre-determined set of questions was used as a focus for the interaction. However, the interviewer pursued ideas from the family members in a conversational style and encouraged them to elaborate on their comments. Both interviews were transcribed verbatim and segmented by idea unit.

The research team video recorded a semi-structured pre-interview with the family about their current reading habits (e.g., "How often do you read?"); what motivates their child to read (e.g., "What systems do you have in place to encourage your child to read?"); and the family's familiarity with, experience with, and thoughts about working with technology for reading (e.g., "If you had a technology that worked with you while you read, what would it do?"). After the pre-interview, the main child was introduced to the robot and instructed on how to begin working with the robot. Once they were ready to begin, their entire interaction was video recorded. After the robot interaction was completed, families participated in a second semi-structured interview (post-). This interview was about the family members' view of the robot as a partner (e.g., "Did it feel like Minnie was alive?"), their likes and dislikes about the interaction with the robot (e.g., "Are there any things you would change about Minnie?"), and whether they thought the robot would be a useful tool for the home (e.g., "If the robot were released to the market today, would you be interested in buying one for your child?").

Grounded theory analysis. All video data was transcribed, coded, and analyzed following a constructivist Grounded Theory approach (Charmaz & Belgrave, 2012). The analysis

began with an open-coding step where numerous informal codes were used to summarize significant idea units in the interview transcripts. These informal codes were evaluated to find emerging themes within the transcripts, and twenty-four formal codes were identified and applied to the transcripts. The reliability of the coding was assessed by comparing inter-rater reliability between coders on 10% of the data and was found to be adequate (Cohen's $\kappa = 0.79$). These initial codes were refined into eight axial codes that combined the formal codes to refine the coding scheme into broader categories, and these categories were further organized into four major themes. The findings below present details of each of the major themes and are followed by a discussion of the interpretation of these findings.

Results

In this section, I report on the findings from the in-home visits with eight participating families. I discuss four main themes that emerged from the analysis. I first describe what I found to be the relationship with reading for each of the main children: their habits, ability, and interest phase. I then detail the three remaining themes that emerged. Each theme is supported with evidence from interview and/or robot-interaction data. Figure 5 describes each of the major themes of the findings.

Throughout the description of the findings, families are numbered 1 through 8 with each member identified as "MC" for the main child in the study, "P" for the parent, and "OC" for another child present during interviews. For example, the main child in family number seven is labeled as "MC7", and the parent for family 4 is labeled as "P4". The researcher conducting the interviews is labeled as "R" throughout. Non-verbal actions, such as nodding their head in agreement, appear between double parenthesis, e.g., ((nods head "yes")), and paraphrasing is indicated by words surrounded by brackets.

Relationship with Reading

Each of the children described their relationship to reading that was consistent with one of the phases of the Four-phase Model of Interest Development.

Development of Interest

Children describe their interaction with the robot as enjoyable, valuable, and capable of improving their ability—all characteristics of *interest development*.

Attribution of Human Characteristics

Children often attributed human characteristics, including emotions and thought, to the robot.

Social Companionship

Children in the study refer to the robot in terms of having “someone else there” to read with.

Figure 5. Summary of each of the themes emerging from the analysis.

Relationship with reading. In recruiting for the study, I initially intended to enroll children with a variety of interest levels in reading. During a short, online, pre-screening questionnaire, I included a question that asked a parent to estimate the amount of time their child spent on reading each week. I believed that this measure would prove useful for inferring a relative interest level but realized soon after I began the visits that this estimate was often not very accurate. Thus, I chose not to make any recruitment decisions based on pre-screening. I instead used pre-interview descriptions of the child’s view and habits towards reading to identify what phase of interest in reading they were likely in. While I do not believe that any of the participants to be categorized in the first and lowest phase of interest development, *triggered situational interest*, I classified two participants (MC1 and MC2) in phase two, *maintained situational interest*; three (MC3, MC4, and MC5) in phase three, *emerging individual interest*;

and three (MC6, MC7, and MC8) in the highest and fourth phase, *well-developed individual interest*. These evaluations were supported by results from each child's FID-RS individual interest survey score. I found that the *phase two* readers had the lowest and third lowest scores (4.5 and 5.4), the *emerging individual interest* readers fell in a middle range between 5.3 and 5.9, and the *well-develop individual interest* readers had all three of the highest scores that ranged from 6.3 to 7.0 (the scale maximum). Based on information gathered during the pre-interviews, I now turn to describing the children at each level of interest in reading.

Phase 4: Well-developed individual interest. Of the three well-developed individual interest readers, one, MC8, had an extreme interest in reading. MC8 reads an exceptional amount (300 or more pages per day), and was described by his parent, P8, as "off the charts." He is such an avid reader that the local bookstore supplies him with "a lot of advanced readers of books each month" to have him "give them an opinion on the books." He described having very little need for a reading technology and struggled to find ideas of what one might do, because he felt no need to support improving his reading ability or motivation to read.

The two other high interest readers, MC6 and MC7, described themselves as having high reading ability, and that they were an "avid reader," and "always loved to read," respectively. While they felt that they were very good readers, they both indicated that they would like to continue to develop their reading ability with a technology that might suggest new books for them. MC6 also added a desire for a technology that would track their reading and provide some level of motivational support, while MC7 mentioned an interest in reading out loud.

Phase 3: Emerging individual interest. The three emerging individual interest readers read between 30 to 60 minutes on an average day and find that they can become engrossed in the right book. However, they often struggle to find new books that interest them and are continually

seeking out new material. For example, MC4 said, “I go out and try to find new books, but I don’t, like, find that many books appealing to me.” This behavior may be due to being reluctant to invest in reading new books, which leads them to re-read many of the books they already have several times. They value reading as a way to learn, believe that they are “okay” readers, would like to “practice and get better,” and appreciate ways of being supported in developing their ability. They also recognize a need for some external motivational support, particularly when they do not connect with a book right away (even if it is just a “nagging mom”). MC3 did not suggest anything he would want a reading technology to do. However, both MC4 and MC5 would like a technology to help them understand and pronounce words while they read and to give them feedback about the book as they read.

Phase 2: Maintained situational interest. Both of the maintained situational interest readers described themselves as capable readers. While both said that they only “like reading a little,” they reported enjoying reading when they really like a book. However, they described different amounts of time spent reading; MC1 reads 30 minutes a day, because this is the goal her parents set for her, while MC2 reads very little outside of what is required for school. They both felt that reading is something that they should do more of but did not prioritize among other activities. Thus, they did not seek out reading unless required. For MC2, this conflict of feeling that he should read more but not really making the time for it appeared in the interview when describing that it is hard for him to find a book. He said, “Yeah I am like looking right now. Well I am trying to get time to look for books. Well I mean I have got a lot of time but...,” indicating that while he feels that he should be looking for an interesting book, he is not actively doing so. Both children mention that tracking their reading with a log has been an effective method of motivation in the past, although MC2 no longer uses any tracking, and both said that logging and

tracking would be welcome features in a reading technology. MC1 also added that she would like a technology that would “Listen to [her] and tell [her] what it thought of the book or what [they] read.” MC2 indicated that he would like a technology that could support understanding by adding illustrations to depict what was happening in the text. Both of their parents mentioned motivational support as something they would like a technology to offer.

This multi-method approach provides theoretically grounded empirical support for the Four-Phase Model of Interest Development that has been called for in the literature. Table 1 summarizes these findings. I now begin describing themes that emerged from observations of the children interacting with the robot and their post-interviews.

Table 1

Summary of Phases of Interest for Study Participants

Participant	Phase #	Phase of Interest	FID-RS Score
MC1	2	<i>maintained situational</i>	4.5
MC2	2	<i>maintained situational</i>	5.4
MC3	3	<i>emerging individual</i>	5.4
MC4	3	<i>emerging individual</i>	5.3
MC5	3	<i>emerging individual</i>	5.9
MC6	4	<i>well-developed individual</i>	6.7
MC7	4	<i>well-developed individual</i>	7.0
MC8	4	<i>well-developed individual</i>	6.3

Note. Possible FID-RS scores range from 1 – 7 and correspond to Likert response levels of *strongly disagree* (1) to *strongly agree* (7).

Development of interest. The initial design of the learning companion robot was heavily influenced by interest development theory, and my analysis found that the children in the study describe much of their interaction in terms of the characteristics of interest development: *positive*

affect (i.e., enjoyment), *value* for the interaction, and increasing ability or *knowledge* as a result of the interaction. They also mention all the specific design elements during interviews and often referenced these in relation to experiencing interest development characteristics. Positive affect was generally mentioned across all participants. All said that they liked something about their interaction with Minnie and described the interaction as “nice,” “fun,” and “cool.” Positive affect was attributed equally across all eight of the design elements that the children mentioned. For example, MC5 said, “I liked how she could recommend books and she commented during the book about different parts.”

Among Phase 2 and 3 children, all eight of the design elements were also described as having value to them. They describe specific aspects of the interaction with the learning companion robot as “helpful” or “important”, and these comments were also evenly distributed across all the elements mentioned. In contrast, phase 4 children were much less likely than those in phase 2 or 3 to talk about their interaction with the learning companion robot as a helpful or valuable experience.

In contrast to children referencing many different features of the robot interaction when describing positive affect and value, only two features were mentioned in reference to improving reading ability. Families believed that Minnie providing comments during the reading (*DE4*) helped to improve reading comprehension. Children felt that Minnie’s comments were a way of “recapping” or helping them see the story from “a different perspective.” Reading out loud (*DE5*) was an element of the interaction that children described as potentially improving their reading skills (e.g., vocabulary and pronunciation). For example, when MC4 was asked about the process of reading out loud, she said that it “helped [her] pronounce [words] better” and this would make her “better at reading.”

Describing the interaction with Minnie as a way to develop reading ability was almost entirely done by phase 3 readers. Children in phase 2 and phase 4 each only mention improving reading ability once and focus more on liking the learning companion robot and how the interaction was helpful to the process of reading but not necessarily their ability to read. This behavior may indicate that the support provided by Minnie to improve reading ability is a good match for children who feel they are good readers but need a little help with both comprehension and reading skill. When the researcher asked the families about improvements or changes they would make to the learning companion robot, those in phase 2 focused on changing the interaction to better support reading ability, while those in other phases mentioned ways of improving ease of use. The detail of this distinction can be seen by contrasting MC4's (phase 3) statement above, that the act of reading out loud would be sufficient practice for her to improve her pronunciation, with MC1's (phase 2) belief that they would want to add features to Minnie that support pronunciation. MC1 said she would want to add this type of feature when they said, "If it was a chapter book, at the end of the chapter [it] would tell you all the words that you got wrong and [you] had to say them."

In comparing children across the three phases of interest, only those in phase 3 (emerging individual interest) seemed to feel their wants and needs for supporting their development of reading ability were met. However, families made many suggestions for additional features to address knowledge and skill building. Some of these focused on improving reading, such as an option to "mostly do reading in [their] head", or "sentences about what happened in the full chapter". Families also often suggested that Minnie be programmed with the capability to provide additional support for other subjects—particularly math and science.

I now assess how well *interest* may be developed as a result of interacting with Minnie by comparing the experiences of children across differing phases of interest in reading. I found that Minnie, as designed, may be best suited for those in an emerging individual phase of interest (phase 3). These children expressed experiencing support for all three characteristics of interest development—positive affect, value, and knowledge or ability development—as a result of their interaction with Minnie, and support across all these areas is important for developing interest at this phase. Minnie may also be appropriate for maintained situational interest (phase 2) and well-developed individual interest (phase 4) participants, although its benefits for those at extreme levels of interest (i.e., MC8) would likely be limited. Their interest in reading did seem to be triggered by their enjoyment of the interaction and the value they found in working with Minnie—both important factors in developing interest in a domain.

Attribution of human characteristics. In order to best promote reading engagement and interest, the robot was designed to act in a social way. The participants' attribution of various human characteristics to Minnie indicated that this goal was achieved. The families described the robot as being able to “look,” “listen,” “talk,” and “understand” as well as having personality characteristics such as being “jolly,” “pleasant,” and “funny.” They also attributed thoughts and feelings to the robot such as feeling “happy,” making “connections” to what you were reading, appearing to have “liked the book”, and seeming to “[have] something to say.” When asked why they got this impression, many referenced the feedback and comments as well as the physical movements made by the robot.

Notions about Minnie's feelings and personality came from both physical and software design. Specifically, Minnie's physical shape (e.g., enlarged rounded head and large eyes)

seemed to influence perception of her personality, and the speech capabilities that were tied to the specific context seemed to give the appearance of thoughts and feelings.

One feature of the learning companion robot that had a significant impact on this impression of human characteristics appeared to be the continuous face tracking during the interaction. The robot was designed to orient its head toward each face detected and include intervals of randomized movements in other directions. MC6 noted that it felt like the robot was “looking” at her, and while MC1 worked with Minnie, her sibling, OC1, sitting near them, noted that Minnie would point her head directly at each of them and other places in the room. They said, “It like looked around the room and saw stuff, and it was looking at me and MC1 a lot.”

Feeling that Minnie could understand was often attributed to what the learning companion robot would say. Families felt that Minnie “knew your name” because she would use the child’s name when saying hello. They also saw her comments during the reading phase to be an indication that she could comprehend the story. For example, MC6 said, “She [Minnie] talked about the whole thing you’ve read and the chapter, cause after I read how someone in one book put up a sign on their door she asked like ‘Oh I wonder why was there a sign on the door?’”

This attribution of human characteristics to the robot is consistent with prior work in the field, and the design of the robot intentionally integrated social behavior in order to further the goal of improving engagement in reading with the robot. I was, however, surprised to find that the social interaction tapped into a strong desire for social companionship while reading.

Social companionship. The combination of the social behavior of the robot with the children’s desire to socially engage while reading produced an effect that I describe as *social companionship*. I did not expect the children in the study to express a desire to socially engage

while reading, as reading is commonly characterized and pursued as an individual activity. However, the idea of social companionship was touched on by most families, with the exception of MC3 and MC8, during the interviews. For the families who spoke about reading *with* someone, a lack of social companionship was cited as a reason that reading could be boring, and reading together was a habit in which many of the families currently engaged. Since Minnie was designed to behave socially, this behavior seemed to help children find social companionship while they read with it.

Social companionship was not only positively discussed by almost all of the families during their interviews but also appeared to be beneficial across all phases of interest. Both of the phase 2 readers felt that it helped them engage with the reading activity. MC1 had complained that reading is usually boring, but she said that Minnie “encouraged [her],” and reading with it was enjoyable because there was someone else there. She also stated that she “liked the company,” because she would “usually read alone.” The other phase 2 reader, MC2, also seemed to find having Minnie there as a social companion while reading to stimulate his motivation to read, when she they said, “Because I mean she helps, it is pretty much like having someone there helping you read. So, like if I am home alone, I can have it sit out and I can, it can help me with my stuff while I am reading.” After this statement, MC2 when on to agree that this help would encourage them to make more time for reading.

The social companionship of reading with Minnie also seemed to be a positive experience for the phase 3 and 4 readers as well, although it took different forms; MC4 liked that reading with Minnie felt like reading to someone younger. MC4 said it was a “fun exchange,” because they, “found it, like, that... my, the voice in my head that I use when I’m reading to

myself sounds different than when I read out loud... It felt like I was reading to a little kid, and, like, helping them understand.”

MC5 related the experience of reading with Minnie to the positive feelings they had while reading with their family, by saying it “felt like it was another person listening and like I could communicate with her.” MC6 found that the social companionship led to better reading, because, “It... kind of just listened to you instead of just you reading by yourself... You actually tried to do really good. Finally, MC7 found that, through the comments while reading, Minnie took on a social companion role similar to MC7’s friends who read the same books as her. She said Minnie could, “kind of comprehend what you were reading it seemed like. And she would, like, make connections just like a friend would do.”

As discussed above, the social aspects of the learning companion robot were not intended as a means to provide social companionship. However, this experience seemed common for the participants and was an effect across all phases of interest. There is also evidence that the added social companionship of reading with the learning companion robot addresses each of the major areas of interest development: increases in positive affect, value, and knowledge and skills in the domain.

Discussion

The four themes that emerged from the Grounded Theory analysis suggest two major design implications for designing a learning companion robot for reading: providing support for interest development across all phases of interest and intentionally designing for social companionship. The findings may also be applied to other academic domains, such as math or science education, and could prove valuable as design considerations for pedagogical agents and

other educational technologies. In this section I discuss these design implications as well as limitations to this study and potential future work.

Supporting interest development. While generating positive affect for a task or area of study is important, researchers note that supporting students to find value in a domain (e.g., reading) and improving knowledge and ability in the task are also critical to interest development (Hidi & Renninger, 2006). As I looked for emerging themes from the data, positive affect, value, and knowledge building were often referenced by families. I found that interacting with Minnie was generally well-liked by all of the families across all phases of interest. This positive experience was attributed to each of the eight design elements of the learning companion robot in some way. The phase 2 and phase 3 children also often expressed finding value in the interaction, much of which was related to the value they felt from increased motivation to read (phase 2) and supporting the development of their reading ability (phase 3). Phase 4 children did not discuss the value of the interaction to them to the same extent, which may be because they value being able to develop reading abilities at a higher level than the learning companion robot was able to support.

The results of the study demonstrate that these eight design elements serve as a good starting point for designing a learning companion robot, or other technology, for reading. The lack of addressing the reading ability development needs of phase 2 and phase 4 learners appears to be the root cause of not fully supporting their interest development. Therefore, to improve future revisions of the robot and to inform the design of other learning technologies that intend to support interest and engagement in reading, I suggest providing a wider variety of deliberate support for improving reading. Suggestions from the families included adding chapter summaries, comprehension questions, and direct vocabulary support for phase 2 readers. Support

for phase 4 readers may include the option to read silently with Minnie and to connect the reading experience outside of the book. Future work should test how adding this additional knowledge support affects the child's experience. Other work might also test the effectiveness of this type of learning companion robot in other domains such as math or science.

Designing for social companionship. While previous work studied the benefits of social robots in educational settings, this study offers new evidence that a robot might play a role as a social companion situated in the home to support reading. I was surprised to find how many of the children simply enjoyed the presence of Minnie as “someone else there to read with.” Most of the children found the interaction with the robot to be very motivating, and the lowest phase of interest readers found that it made reading less boring. Children also attributed increased focus and attention to their reading, improved reading comprehension as a result of reading out loud, and a desire to include Minnie and the feeling of social companionship in other parts of their educational and home experiences. The ease with which the children in the study seemed to feel a social companionship with Minnie was due in part to the strong attribution of human characteristics to the robot. The families described Minnie as fun, pleasant, and nice, and they could picture including the robot in family reading time. They felt that she could see and understand them and knew what they were reading about. This finding suggests that when designing a social robot as a learning companion, it may be beneficial to more deliberately leverage the benefit of the social companionship that can result. However, further study is needed to better understand this phenomenon and the influence it has on a child's engagement in an educational task.

Limitations. While these findings help to better understand the use of a learning companion robot for reading, there are several limitations to the study. First, the generalizability

of these findings is limited due to the small sample size and the geographical region from which it was drawn. A significant limitation is a lack of children at the lowest phase of interest in the participant group, which precludes drawing conclusions across the entire spectrum of interest development. Future studies should deliberately seek to include these very low interest students to better understand how to design for this population. The study was also only conducted with children aged 11–12, and the results may differ for different age groups. Having only interacted with the robot for a short period of time and only allowing one child to directly interact with Minnie may have also influenced how the users report their experience. Therefore, future studies should increase the *breadth* (i.e., a larger sample, from a larger area, made of a broader range of ages and interest phases) and *depth* (i.e., longer period of interaction with the robot including more family members) of this investigation. Finally, the robot was only studied in one educational domain, in one medium (a robot), and in the homes of the families. Theory and practice would benefit from observing the experience of using this type of learning companion in other areas of study, using other forms of educational agents, and in other education settings (e.g., classrooms or informal learning environments).

Conclusion

To further explore the educational use of robots, this study investigated the use of Minnie, a learning companion robot, as a technology probe to examine the reading habits of children and how this type of technology might be used by families in their homes. Children interacted with Minnie during an in-home visit and families participated in pre- and post-interaction interviews in order to delve into these ideas, to help evaluate the initial design, and to inspire ideas for future design. Four major themes emerged from the Grounded Theory analysis: (1) the reading habits of participants aligns with three specific phases of the Four-phase Model of

Interest Development; (2) interaction with the robot provided support for the development of interest in reading; (3) several human characteristics were attributed to the robot, including emotions and thought; and (4) the robot was embraced as a social companion during the act of reading.

Based on these findings, I recommend the use of the eight design elements described in this study for similar learning technologies. I also recommend that future designs include additional support for improving reading ability that better address the needs of children with a wider range of phases of interest and ability. Finally, the finding of the social role of the learning companion robot and its potential impact as a mechanism for developing interest in reading requires further investigation. This study provides practical design recommendations for the creation of educational robots and may also inform research and design in other areas of educational technology. Finally, the finding that a robot can be seen as not simply a facilitator for learning, but as a social companion to children engaged in an educational task in their home, has implications for both interest development and human-robot interaction literatures, because it demonstrates the possibility for a robot to assume the role of a meaningful social other while learning.

Study 2: Transforming the In-Home Reading Experience Over Time with a Learning-Companion Robot

Introduction

The results from Study 1 demonstrate the potential of providing a social robot as a learning companion for children. A social robot that augments in-home learning activities, such as reading, to capitalize on the benefits of socially supported learning can have a powerful impact on promoting interest in reading and developing skills for reading fluency and comprehension. While Study 1 demonstrated this potential, developing the type of social experience needed to have an impact on developing interest requires a social robot capable of cultivating a long-term social relationship with a child. This relationship requires establishing and maintaining a social presence over time. 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. As emotional expression is an essential aspect of social interaction and connections (Frijda & Mesquita, 2003), the perception that a robot has emotions can indicate a deeper social connection between a human and a robot (Breazeal, 2003; Breazeal & Brooks, 2002).

Social connections with a robot over time 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 (Breazeal, 2002). 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 (Kidd, Taggart & Turkle, 2006). 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 (Leite, Martinho, Pereira, Paiva, 2009). 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 (Kidd & Breazeal, 2005).

Several previous studies provide design guidelines and demonstrate the promise for long-term interaction with social robots (see Leite, Martinho, and Paiva, 2013, for a review).

However, to date no such studies of academic activity, such as reading, have been conducted in an in-home setting and over extended period of time (see Belpaeme et al. 2018 for a review of robots in education). In this study, I address this gap in the literature, expanding on the results of Study 1, 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?

Additional Design Aspects of the Social Robot

In Study 1, Minnie's behaviors were designed based on eight evidence-based design guidelines (see items 1-8 in Figure 2 in section 1) from current interest development and human-robot interaction research. For this study, I identified and included one additional design element (see item 9 in Figure 2) based on recommendations from Leite, Martinho & Paiva (2013), and Kanda, Sato, Saiwaki & Ishiguro (2007). The new design element highlights the way in which the robot should present emotion and personality to users over time. That is as Minnie makes comments about the books as the child reads out-loud, the robot can use speech that may be

perceived by the child as the emotional responses, feelings, or personal history of the robot. Based on the original design elements, the comments are designed to demonstrate enjoyment and interest in the reading, and to summarize and predict the activity in the books. I now explicitly designed these comments to also slowly, over several interactions, portray emotional responses and feelings or to convey some connection to a fictitious personal life for Minnie (DE9). For this study, I added 15 new books and over 600 unique comments tailored to the reading at specific pages of the now 25 books included in the library. Without being repetitive or predictable, Minnie slowly weaves elements of her personality and backstory into the interactions. In other words, it takes time to get to know Minnie, which may help sustain and deepen social connections over time.

Method

The goal of Study 2 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 male, 14 female; ages 10–12) participated following child assent and parent/guardian informed consent obtained after the nature and possible consequences of the studies were explained and were randomly assigned to a *robot* or *control* condition. The robot condition used a modified version of the Minnie robot designed in Study 1 to facilitate reading activities over the course of two 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. Figure 6 depicts children engaging in the reading activities in the robot condition (Figure 6, left), and the control condition (Figure 6, right). For this study, I chose a reading task similar to reading practice activities that might be assigned to early adolescent children as homework by a

teacher to improve fluency. I 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 one of 25 fiction and non-fiction books provided. The activity was either completed by children as a reading log in a *paper-based activity (control condition)* or facilitated by the *learning companion robot (robot condition)*. To examine differences in the reading experience over time, I randomly assigned children aged 10 to 12 to one condition for a two-week long field study conducted in-home during their summer break from school. To simulate voluntary summer reading activity, children were told to read at their own discretion and that there would be no consequences for not reading. A sample page from the control condition reading packet is included in Figure A1 of Appendix.



Figure 6. Children engaging in study reading activities. (left) A child reading out loud from the introduction book *Talking with Minnie* to the robot during the first visit, and (right) a child in the control condition reading 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).

Data sources. During the first visit to the child’s home, children completed a questionnaire including the FID-RS individual interest-in-reading scale (prior reading interest; see Appendix Table A1) prior to engaging with the robot and a short interview about their initial impressions (*1st-visit interview*) and a situational-interest scale (*initial situational interest*; see

Appendix Table A2) after reading with the robot or paper-based activity for 15–20 mins. The robot and 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 hand-held 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 (*2nd-visit interview*) and a questionnaire including the situational-interest scale (*post-situational interest*). To reduce any potential socially desirable response bias (Havermans, Vanassche & Matthijs, 2015), before each set of self-reports, the researcher emphasized to children the “importance of telling the truth about how they feel,” and that the study needed their “honest opinions to understand how to best design the robot.”

The daily reading times were collected from reading usage logs. The 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 was considered as part of the acclimation period and excluded to control for novelty effects. All data-collection procedures were designed in collaboration with and approved by the University of Wisconsin–Madison Institutional Review Board (IRB). 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 non-study activity.

Statistical analyses. As in Study 1, all interviews were video recorded, transcribed verbatim, and coded using a Constructivist Grounded Theory approach (Charmaz & Belgrave, 2013). Again, coding began with an initial round of open coding to describe the content of each interview. I then conducted a round of focused coding of the initial codes to identify generalized

themes within the data and identified 20 axial codes from focused coding that were applied to the transcripts of each interview. Interrater reliability was tested on 10% of the total sample and was high ($\kappa = 0.85$) based on estimates with a Cohen's Kappa 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 FID-RS 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 alpha greater than 0.70 as criteria (Crocker & Algina, 2006).

All statistical tests used an alpha 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, homoskedasticity, and normal distribution of residuals.

Results

In this study, I utilize a mixed-methods reporting of the reading experience. I first compare *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. I then consider *qualitative* data from interviews after an initial introduction to the robot or paper-based activities (1st-visit interview) and a follow-up interview after two weeks of completing activities (2nd-visit interview).

Synopsis. In brief, 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 Figure 7A and 7B). I also found that more children felt motivated to read and improved reading comprehension with the robot (Figure 7C), and at the end of the study, more children expressed motivation to read with the robot and that the robot had emotions or a personality (Figure 7D), indicating a transformation of reading into a social activity that scaffolds key dimensions of interest development, including motivation and comprehension.

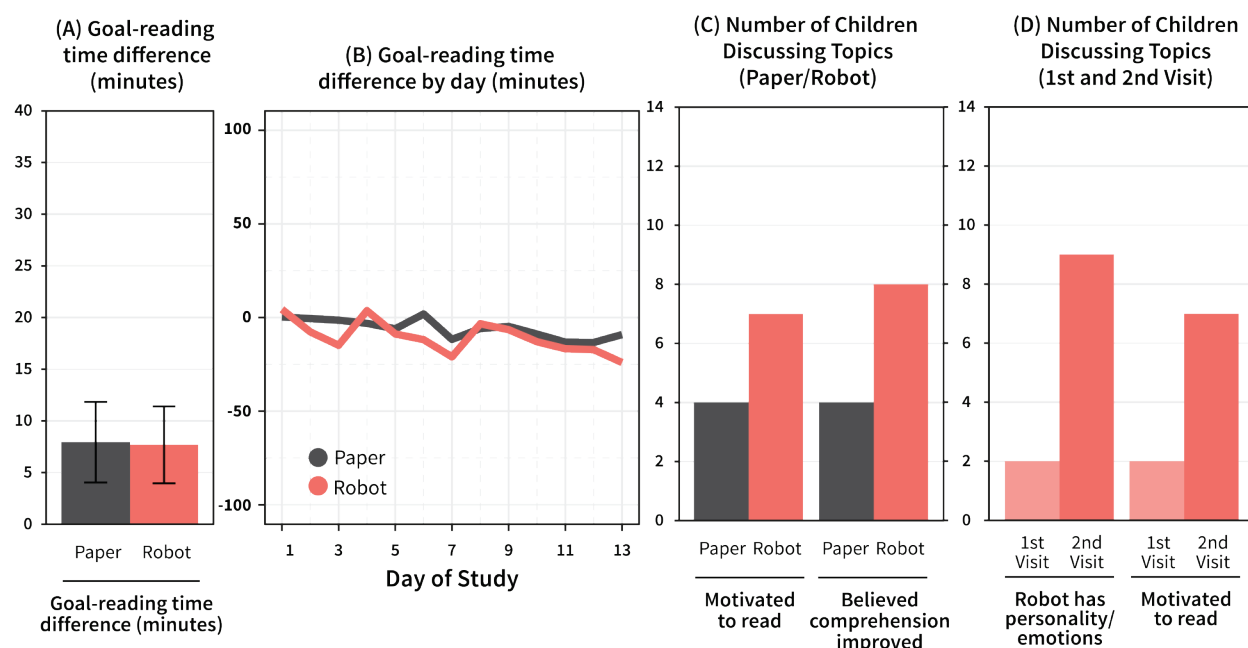


Figure 7. Summary of results in synopsis. Reading goal to reading time differences on average (A) and over time (B). (C) Differences in reporting motivation to reading and improved reading comprehension. (D) Feelings, based on 1st-visit and 2nd-visit interview responses, that the robot has emotions and in motivation to read for the robot condition. Error bars in (A) represent SE.

Quantitative results. Children in the robot condition read on average 8.17 days ($SD = 2.82$), for 17.67 minutes ($SD = 15.08$) per day, with a reading goal of 25.35 minutes ($SD = 13.80$) each day. Those in the control condition read on average 8.42 days ($SD = 3.78$) for 23.76 minutes ($SD = 17.36$) per day, with a reading goal of 31.71 minutes ($SD = 16.48$) 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 to goals ($t(22) = -0.05, p = 0.96$ (see Figure 8B). Figure 8C demonstrates 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 Figure 8A) revealed no significant difference in initial situational interest between the robot condition ($M = 5.44, SD = 1.45$) 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 control condition ($M = 5.40, SD = 1.22; t(22) = 0.50, p = 0.62$). There was also no differences between initial to post-situational interest scores for the robot condition ($t(11) = 0.92, p = 0.38$) or control condition ($t(11) = 0.54, p = 0.59$). A comparison of prior individual interest in reading, measured before any study activity, and individual interest in reading after completing the study also revealed no differences over time or between groups. For those in the control group their prior reading interest ($M = 5.77, SD = 0.71$) and reading interest after the study were not significantly different ($M = 5.69, SD = 0.91; t(11) = 1.50, p = 0.16$). For those in the robot group their prior reading interest ($M = 4.93, SD = 1.27$) and reading interest after the study were also not significantly different ($M = 5.05, SD = 1.19; t(11) = 1.27, p = 0.23$).

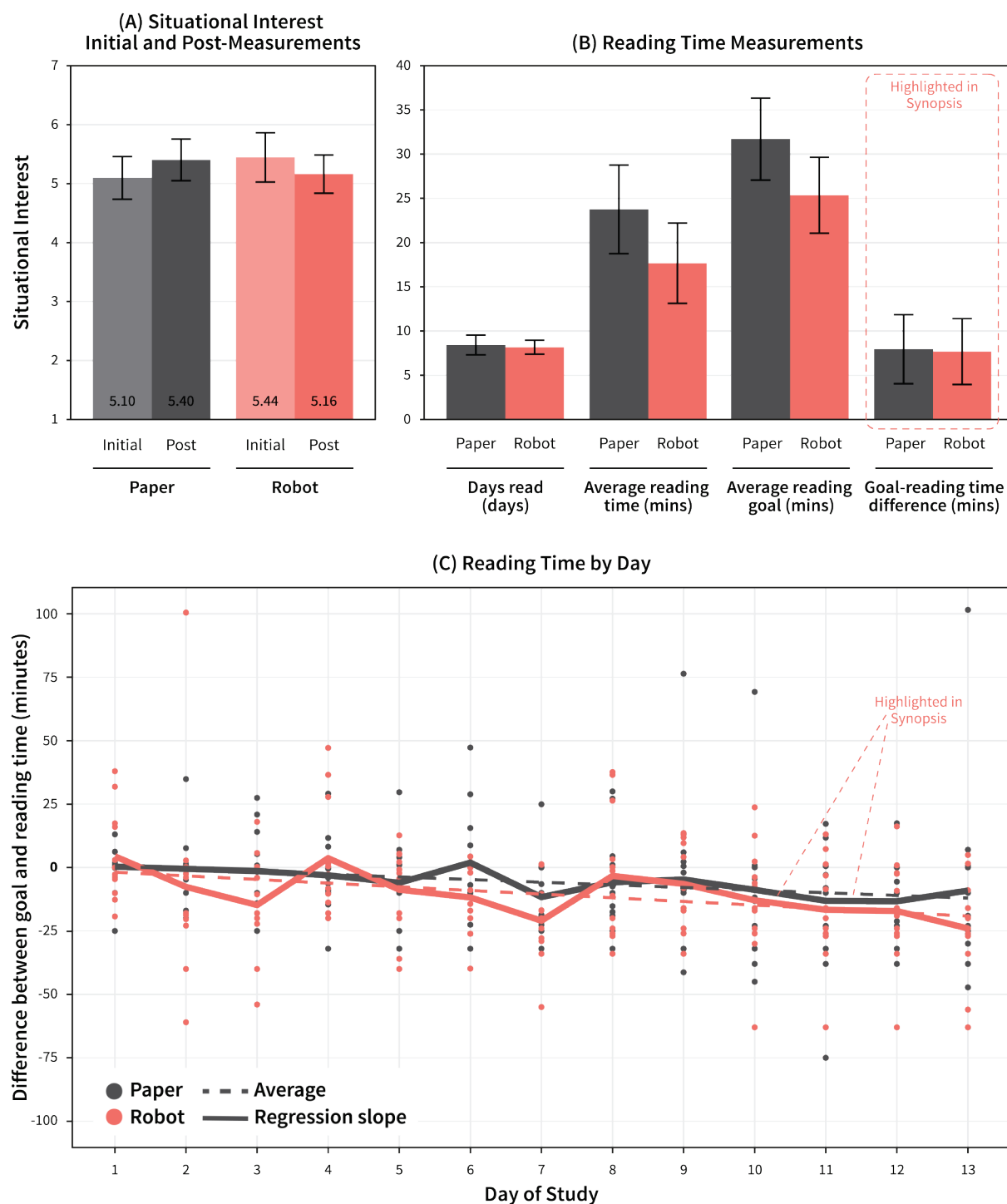


Figure 8. Quantitative results by condition. (A) The average number of days read, reading times, and reading goals, as well as the average difference between the reading goal and time. (B) initial and post-situational interest scores. (C) Reading times compared with reading goals by day, where each point 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.

I then conducted two regression analyses to examine usage patterns and found similar reading engagement in both conditions (Figure 9). 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

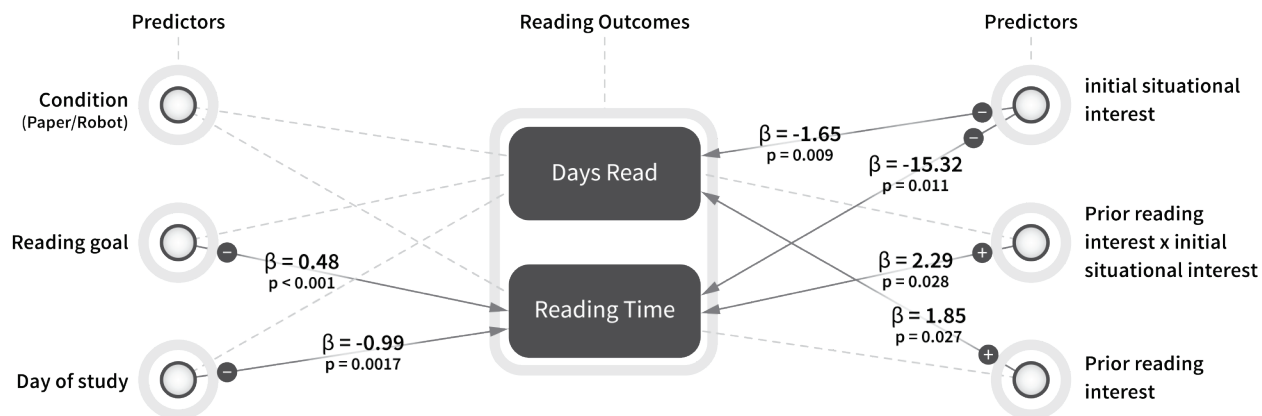


Figure 9. Regression analysis summary. Center and outside nodes represent outcome and predictor variables used in the regression models, respectively. Solid lines with arrows and dashed lines represent statistically significant and nonsignificant contributions, respectively.

number of days read: prior interest in reading ($\beta = 1.85$, $p = 0.027$) and initial situational interest ($\beta = -1.65$, $p = 0.009$). I also tested all two-way interactions between the variables and found no significant effects. In this model, each 1-point increase in prior interest in reading predicts reading for 1.85 additional days, and each 1-point increase in initial situational interest predicts reading for 1.65 fewer days. While 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 (See Figure 9). 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 ($\beta = -0.99$, $p = 0.0017$), reading goal ($\beta = 0.48$, $p < 0.001$), and initial situational interest ($\beta = -15.32$, $p = 0.011$). The interaction between prior reading interest and initial situational interest was also a significant predictor ($\beta = 2.29$, $p = 0.028$) and was included in the model. This model suggests that for every increase of 1 minute for their reading goal, children read for an additional 30 seconds, and for each day of the study, students were likely to reduce their reading time by nearly 1 minute. 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. In other words, 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, study condition did not have a significant effect on the 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. I present the qualitative results reported here in two sections. Figure 10 shows comparisons between groups for select codes from 1st-visit and 2nd-visit interviews that are relevant for this report. The first compares the reading experience of children who read with

the robot (*robot* condition) to those who completed similar paper-based guided reading activities (*control* condition). The second presents changes in how children describe their experience with

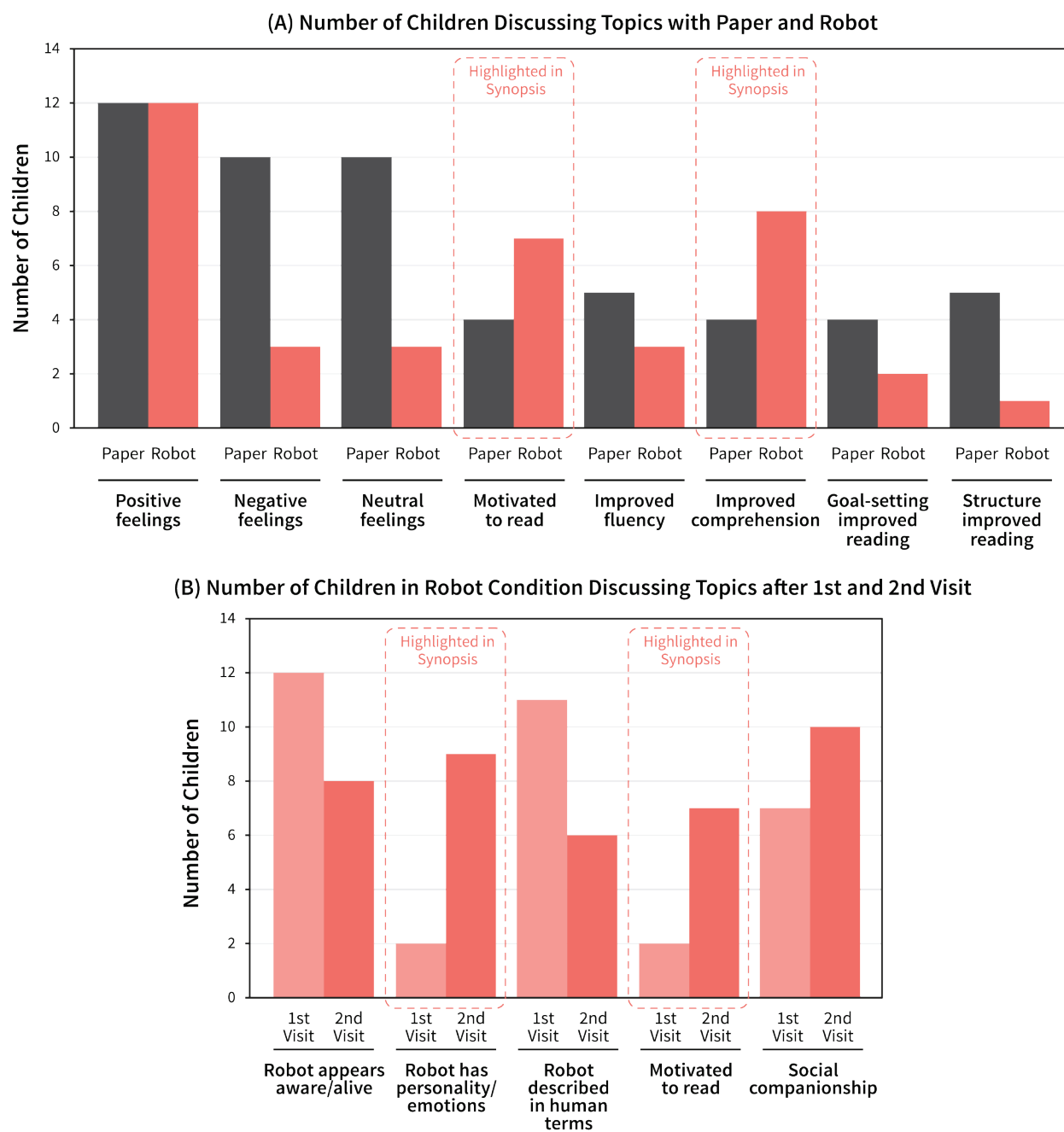


Figure 10. Counts for qualitative coding. (A) Total number of children with each code in post-interviews for select variables by condition. (B) Total number of children in the robot condition with each code in 1st-visit and 2nd-visit interviews for select variables.

reading with the robot over time. Both analyses focus on codes of 1st-visit and 2nd-visit interviews. Details of count data and definitions for each of the codes can be found in Table A3 and Table A4 in the Appendix. Throughout this report, I use participant IDs (e.g. C111 or R302) to attribute direct quotes to the children who said them.

Comparing conditions. Results from the 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, while those in the robot condition discussed improved reading comprehension and increased motivation to read. Figure 10A 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 explains, “I got to read books that... I have never heard of.”

While their descriptions of the reading activity were overall positive, children in the control condition had a larger number of negative (10) responses to questions about their experience, and few, only four, suggested that the activities motivated them to read more. While reading out-loud and the structure of the reading activities were cited as ways to improve their reading ability, 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 was 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 2nd-visit 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 understand what was happening in the book better. 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 since, “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 suggests, “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 (4), 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, while 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, as 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, while the control condition felt that the activity improved fluency.

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 two weeks, they began to describe the robot in terms of its emotional responses and personality. Figure 10B shows the codes for interview responses after the 1st and 2nd visit for each child in the robot condition.

Initial (1st-visit) 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 the 1st-visit 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 1st-visit 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 2nd-visit 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

This study contributes 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. Most importantly, the 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 does the experience of completing guided reading activities change when facilitated by a learning companion robot? The quantitative measures show that children in both conditions demonstrated and reported high engagement and interest in the guided reading activities. The 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 promotes shared cognitive activity and contributes to improved comprehension and motivation to read (Guthrie & Klauda, 2014). Also consistent with prior work, children appeared to find their interactions with Minnie to be a *social* experience (Leite, Martinho, Pereira & Paiva, 2009; Kanda, Sato, Saiwaki & Ishiguro, 2007). 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 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 does the experience of working with a learning companion robot for in-home reading change over time? The results demonstrate 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.

The quantitative results revealed a stable level of individual interest in reading for both groups over time, similar situational interest for 1st-visit to post study measures, and a negative effect of time on reading, with a small decrement (approximately 1 minute) of reading time predicted each day. While 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 (McKenna, Kear & Ellsworth, 1995) and that children read during their summer break. Since the guided reading activity itself was a successful reading intervention, I 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 impact reading engagement. Additionally, 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 (Frijda & Mesquita, 1994; Breazeal & Brooks, 2005). I attribute a lack of a more dramatic decrease in reading than the control condition due to technical challenges to the social support that the robot provided and to the deepened connection children had with the robot.

The comparison of 1st-visit and 2nd-visit 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 (Bergin, 2016; Guthrie & Klauda, 2014), 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 (Hollan, Hutchins, & Kirsh, 2000).

Rather than wearing off over time, the qualitative data provides 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 and 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, Martinho and Paiva (2013), 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 (Frijda & Mesquita, 1994) and between humans and robots (Breazeal, 2003; Breazeal & Brooks, 2005), and is indication of a deepening social connection between Minnie and the children.

Summary and Limitations. In the coming decades, robots will become increasingly engrained 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 transform the in-home reading experience such that children sustain reading engagement over time; feel that they understand more of what they are reading; and feel that they are sharing this experience with someone who is interested in their efforts. This study demonstrates how social robots might be incorporated into learning activities at home to reach their potential as crucial educational and learning supplements for the future.

The design elements included in the development of this social robot should inform other researchers and designers of learning technologies and activities and the findings 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.

While this study makes a significant contribution to the field, the findings are limited by several factors. First, due to the small sample, strong generalizable claims based on these results cannot be made. Larger sample sizes involving quantitative data are necessary for more conclusive claims. Second, the length of the study may be too short to make measurable differences in interest and behavior. These results demonstrated a stable level of individual interest in reading over the course of two weeks for both conditions, and this length of time may not have been sufficient to have a measurable impact on individual interest. 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 timescales. Third, the study is limited in examining children aged 10–12 during their summer break. This age group was selected for this study, because social connections with a robot may peak at this age (Kahn et al., 2012), but how these results generalize to other age ranges is unknown. Furthermore, in this study children do not have the usual time constraints of school, since they participated during their summer break, and interactions during the school year may be different. There is also a limitation in interpreting the interaction between high initial situational interest and low individual interest, because of the small sample. I suggest that future work explore this interaction in more detail to interpret and examine the findings. Finally, time-on-task served as the 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 is challenging, methodological developments might enable the use of such measurements.

The findings are also influenced by the choice of reading activities, method of delivery of those activities for the control group, and technical problems. 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. I included a robust control condition to avoid a “straw man” comparison, but 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 including misread AprilTags or accidental shut-downs, 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, in this study, the 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 over time. The 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 towards this good.

Study 3: Supporting Interest in Science Learning with a Social Robot

Introduction

One aspect of learning that a social robot may be especially useful for is the support of in-home science learning. In-home learning has long been an established part of school-based education, and homework completion and accuracy contribute to academic performance (Cooper, Steenbergen-Hu & Dent, 2012), particularly in precollege math and science classes (Fan, Xu, Cai, He & Fan, 2017). While reading from a textbook is a common homework assignment for middle school science classrooms, many middle school students find textbook reading boring and difficult (Guthrie & Klauda, 2012). Including socially situated interest scaffolds addresses this problem by improving a student's situational interest in textbook reading, creating a path to promoting learning and individual interest in science. To support interest during science textbook reading, Guthrie and Klauda (2012) suggest supporting student self-efficacy with supplemental materials, demonstrating the value of reading a textbook for understanding the content, and using social interaction around reading. There is also evidence that including value and relevance connections while learning from a science textbook have a positive effect on perceived value and topic interest in the content (Zambrano, Lee, Leal & Thoman, 2018). This prior work suggests that middle school students' situational interest and learning in science would benefit from reading a science textbook with a social robot that is designed for socially situated interest scaffolding.

Studies 1 and 2 of this dissertation found that children reading with the learning companion robot, Minnie, at home made a social connection with the robot and described liking the activity because the robot acted as a social companion with whom they could share the reading. The social connection made with the robot appeared to positively influence the child's

interest and was found to deepen over a period of two weeks. These results suggest that augmenting existing learning activities can be a feasible and effect means of integrating a social robot with existing curriculum to support classroom educational goals at home. While the work from studies 1 and 2 is promising, several of the limitations are highlighted in those studies demonstrate limitations in the robot's ability to provide socially meaningful interactions. First, the robot used a classic unexpressive text-to-speech engine that children found detracted from the reading experience. Second, these studies included a small sample size and did not compare experiences between two similar, but distinct, robots. Third, the studies only considered the student experience and their situational interest while reading with the robot and did not examine learning as an outcome of the interaction. These limitations reduce the study's capacity for more generalizable claims and does not investigate whether it is the socially adept activity of the robot or simply the effect of having any robot that drives social connection-making, the development of interest, or learning. Finally, the studies have been limited to reading activities structured around casual reading of popular fiction and non-fiction books. It may be easier for the robot to establish a social connection and promote interest and learning while sharing this casual type of reading experience than in the context of reading an academic textbook.

In this study, I expand on findings from Studies 1 and 2 to further the understanding of learning and interest development with a social robot during a shared reading experience of academic content in science. I examine the ability of a socially adept robot to promote social connection-making, situational interest, and learning in the context of science textbook reading as compared to a similar, but socially neutral, robot. I conducted this examination as a randomized controlled experiment as a first step in assessing the feasibility of a socially adept

robot to positively affect interest and learning in science that can later be tested in more authentic settings, as in studies 1 and 2. In this study, I posited and pre-registered the following hypothesis:

Hypothesis. Interacting with a socially adept robot will result in greater social connection-making with the robot, situational interest, and learning for children reading a science textbook when compared to a socially neutral robot.

Method

To explore the effects of socially adept behavior from a robot learning companion on social connection-making, situational interest, and learning in the context of science textbook reading, I conducted a laboratory study in which participants were asked to read a science textbook with the learning companion robot, Minnie. The robot was programmed to demonstrate interaction behavior that was either socially adept or socially neutral. The socially adept robot incorporated many of the design elements from studies 1 and 2 as social interest scaffolds, and the neutral robot reduced the use of the elements where applicable. In the following paragraphs, I describe the additional design features of the robot, the experimental conditions, the design of the robot's comments, and the selection of reading materials. I then explain the procedure and evaluation measures.

Robot design. For this study, Minnie (See Figure 11) was modified to improve the interaction methods for the robot by adding a 7-inch touchscreen to the robot to replace the RFID inputs used in the earlier studies. To do so, I modified the 3D-printable files to set a mounting space for the camera near the top of the torso, extruded a mounting plate from the front torso of the robot and added a custom case for the 7" screen to connect to the mounting plate. The touchscreen was used to display the graphical user interface (GUI) with a large image across the top three-quarters of the screen and five interactive color-coded buttons along the bottom quarter.



Figure 11. Child scanning an AprilTag with the redesigned Minnie robot, by pointing the textbook towards the robot’s camera (red circle on robot torso).

Each colored button also included the text indicating its function. The child could indicate “yes” or “continue” with the green button, “no” or “stop” with the red button, “repeat” with the blue button, “Pause” with the yellow button, and ask for “help” with the purple button (“help” was disabled for this study).

General Interaction Design of the Robot. In both conditions, the interaction with Minnie begins with the child reading out-loud from a modified version of the introductory book that is used in studies 1 and 2 to demonstrate how to interact with the robot. After the introductory book, children are then asked to read, out-loud, 13 pages of text from a middle school physics textbook (Padilla, Cyr, Miaoulis & Griffith Jones, 2005) that has AprilTags embedded on each page (See Figure 12). The robot tells them that reading this section is their goal for the day and to begin when they are ready. As the children progress through the book, they scan AprilTags on each page (See Figure 11), and the robot responds with preprogrammed comments that correspond to the material on that page. These comments include discussing the

main text that the child is reading, directing the child's attention to illustrations on the page, or asking them to complete small activities in the textbook (See Figure 12). There are also two comments during the reading where the robot will tailor the comment to incorporate one of the child's topic preferences from their user profile. At the end of the reading activity, the robot indicates that the child completed their reading goal and shuts down.

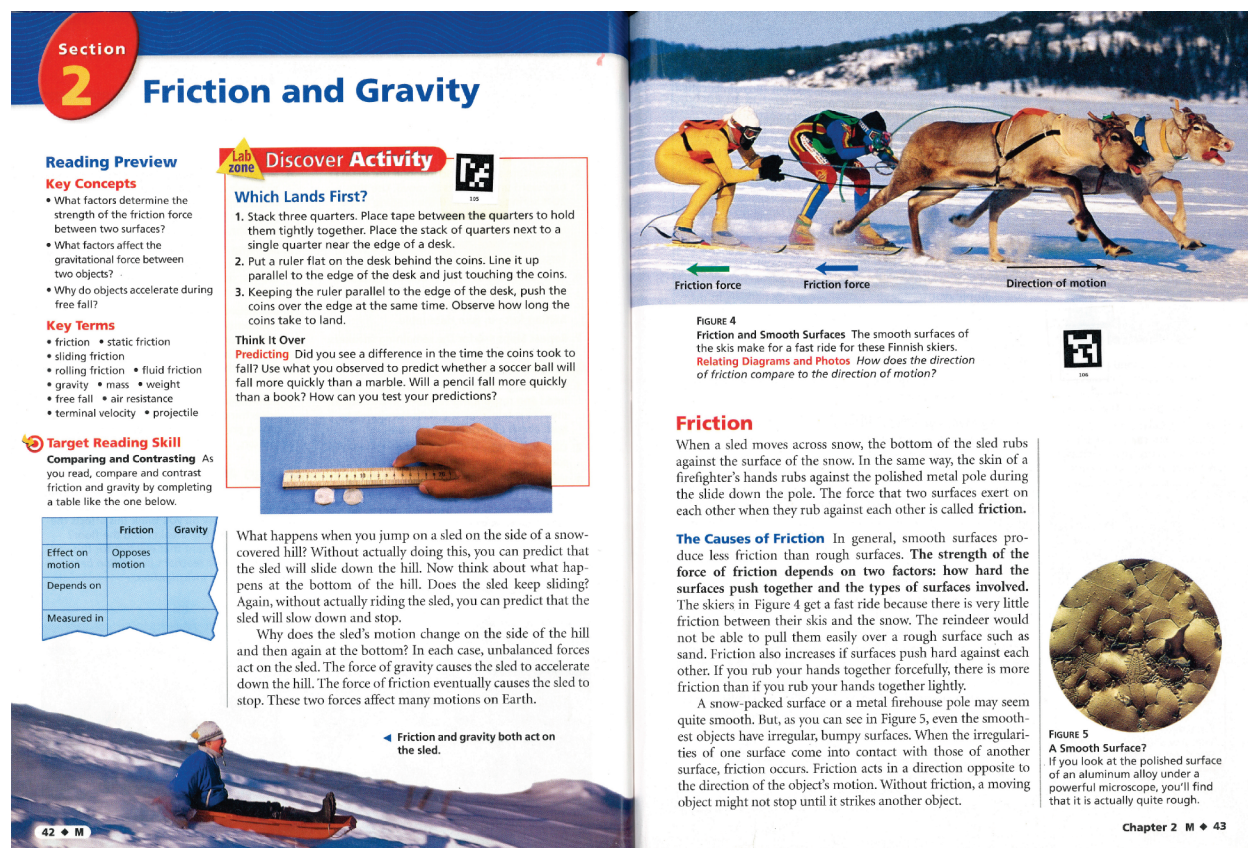


Figure 12. Pages from the middle school physics text. The left page includes an AprilTag at the top right of the text and a hands-on “discover activity” to be completed during the interaction. The right page includes an AprilTag that prompts variable comments related to the image above.

Comparing Robot Conditions During Interaction. During the interaction, the learning companion robot is programmed to behave according to one of two conditions. In the socially adept condition (treatment condition), the robot behaves according to social design principles identified in prior work, including the following:

1. *Expressive speech*: Using a natural and expressive speech synthesis tool, the Salli voice from AWS Polly ⁸, I prerecorded each comment for the socially adept robot and tested each for accurate pitch, tone, and expression (Kory Westlund et al., 2017).
2. *Nonverbal cues*: The robot moved its head and eyes to track the position of the child and to make eye contact using facial recognition software; averted its gaze at semi-regular intervals during interaction to avoid overly long eye contact; and averted its gaze prior to speaking in instances when the comment should be received as thoughtful (Mutlu, Kanda, Forlizzi, Hodgins & Ishiguro, 2012; Andrist, Tan, Gleicher & Mutlu, 2014).
3. *Personal comments*: Over the course of the reading activity, the robot makes comments that incorporates personal connections and reactions to the reading based on a fictional back-story, demonstrates interest and enthusiasm for the reading, refers to itself as a partner in the reading, and calls the child by their name (Leite, Martinho, Pereira & Paiva, 2013; Lim, Hong, Lee, Suh & Beetz, 2013, Kanda, Sato, Saiwaki & Ishiguro, 2007).

In the socially neutral robot condition (control condition), the robot followed the same interaction protocol as the robot in the treatment condition, but I removed the socially adept behaviors. All speech in the control condition was synthesized using the SVOX Pico ⁹ text-to-speech, used in studies 1 and 2, to provide clear speech that is unexpressive in tone and pitch. The robot does not track the child's face during their interaction, nor does the robot use gaze aversion in conjunction with any spoken comments. Finally, the robot's comments were revised to remove any personal connections or emotions from the robot, such as referring to the robot's fictional back-story or showing enthusiasm for reading. The robot also does not refer to itself as

⁸ <https://aws.amazon.com/polly/>

⁹ <https://packages.debian.org/source/jessie/svox>

a partner in the activity, such as stating “you should keep reading,” instead of “we should keep reading,” nor does it refer to the child by their name. Each comment for the socially neutral robot maintained the general content of the comment as written in the socially adept robot condition (e.g., both conditions include comments that direct the child to look at a picture or re-phrasings of a key portion of the text on the page) and is similar in length of speech as in the treatment condition. While I removed as many socially adept behaviors as possible to create a contrast between conditions, intermittent blinking of the robot’s eyelids and small semi-randomized head motions during the interaction ensured that the children were aware that the robot was functioning properly in both conditions. When either an AprilTag is scanned or a button is pressed, the robot blinks and makes a “bleep” noise to indicate receiving the input.

Robot Comments. Each robot comment was carefully designed to appear as if the robot were following along with the reading that the child is conducting, and each corresponding AprilTag is placed in proximity to the location of the text or graphic to which the comment refers. For example, for the page on the left side of Figure 12, scanning the AprilTag on that page prompts the child to complete the “discover activity” immediately to the left of the tag. For each comment, a control and treatment condition version are written where I controlled for length of the comment, basic content of the comment, and any cognitive supports included in the content.

To illustrate how the robot provided comments during the reading activity, I provide an example of the robot comments from one page of the textbook. On page 43 of the textbook (Figure 12, right page) there is a figure that includes an image of Finnish Reindeer Skiers in action to demonstrate the effect of friction on a smooth surface. For this page, I placed an AprilTag just below this figure and when the tag is scanned, the robot selects one of ten

comments pre-programmed to relate the image in the figure to a topic preference for the child. In this case, if the child indicated that they prefer to read about sports during their topic sort, the robot's comment makes a connection to the sport depicted in the image. In the control condition, this comment read, "The skiing in this picture is a unique sport called Reindeer racing. The force from the reindeer must be greater than the force of friction from the skiers," and in the treatment condition, this comment read, "Racing with reindeer! What an incredible sport. I bet the force from the reindeer must be greater than the force of friction from the skiers." Both comments tailor the content to the reader's topic preferences, but only the treatment condition uses language that is personal and enthusiastic.

Science Textbook Reading. The science textbook was the book titled, "Motion, Forces, and Energy," in the Prentice Hall Science Explorer series (Padilla, Cyr, Miaoulis & Griffith Jones, 2005). This book was chosen because it is a commonly used textbook for U.S. middle school (7th and 8th grade) science classes and is written at a reading level appropriate for 10–12 year-old children, but it was unlikely that the sample would be overly familiar with the content, as none had begun their 7th grade year. For the study, children read section 2.1, Nature of Forces, that covered an introduction to forces including a definition of force, balanced and unbalanced forces in two-dimensions, and friction and gravity. There were two activities in this section that the robot asked the children to complete. Activity materials were provided for the child by the researcher, and after each activity the robot added clarifying comments designed to support comprehension of the activity outcomes. For example, on page 42 (See Figure 12, left page) the robot prompts the child to complete the "discover activity" on the page. The activity involves the child placing two different sized stacks of quarters on the edge of a table and pushing them off simultaneously to observe which falls faster. Since Newtonian Physics would

determine that both stacks would fall at the same rate, for clarity, the robot is programmed to comment after the activity that both stacks of quarters fell at the same time.

Procedure. Participants ($N = 63$) were children from Madison, WI (ages 10–12; $M = 10.9$; 36 male, 27 female) who had not begun their 7th grade year. Children were randomly assigned to either the treatment or control condition. One child in the control condition could not complete the study due to technical problems with the robot, and four children (two in each condition) did not complete all study activities in the time allotted for the visit. Data from these five participants were removed from analysis, leaving 29 children in each condition. Children completed study activities in a campus lab office after parent consent. Parents of the children were compensated \$25 USD for the study, and study protocols were reviewed and approved by an institutional review board.

Each participant began the study by completing a pre-test to assess prior knowledge of the physics concepts included in the reading, followed by measures of individual interest in science and reading and a reading ability assessment. Children then followed the robot interaction protocol that included reading the introduction book and 13 pages of the textbook chapter. After completing the reading session with the robot, children were asked to complete a concept-map activity, a survey of their social evaluation of the robot, a post-test to assess learning from the reading activity, a survey of situational interest, and provide demographic information. Finally, children were interviewed about their experience with the robot. In this analysis, I include results from quantitative measures from the study. All qualitative data are currently undergoing further analysis and will be reported in detail in future publications. All measures are described in detail in the next section.

Measures.

Learning measures. I administered two types of assessments to estimate content knowledge for each child. The first was a content knowledge test similar to classroom quizzes commonly administered to assess a child's understanding of academic content. The content knowledge tests in this study consisted of 12 questions (9 multiple-choice and 3 open-ended) designed for the study to be balanced in complexity from basic comprehension to synthesis Bloom & Heyns, 1956) and align with the science content in the textbook (See Appendix Table A5). Two similar versions of the test were created to be used as either pre- or post-tests. The test order was randomized to control for test difficulty. Each question was scored on a scale of 0-1. Several multiple-choice items had more than one correct answer choice. Partial credit was given for selecting each correct answer choice, and no penalties were given for incorrect selections. Open-ended questions were scored by a researcher using a scoring rubric. Inter-rater reliability was tested for 20% of the data and found to be sufficient for all three items ($\kappa = 1.0, 0.85, 0.88$). Pre- and post-tests were scored by summing points across all items with a range of possible scores from 0 to 12.

Since this type of content knowledge test often reflects a shallow understanding of content knowledge that can be easily repeated from reading materials, I also chose to incorporate a concept-map activity (See Figure 13) to assess deep understanding of the interconnection between ideas.

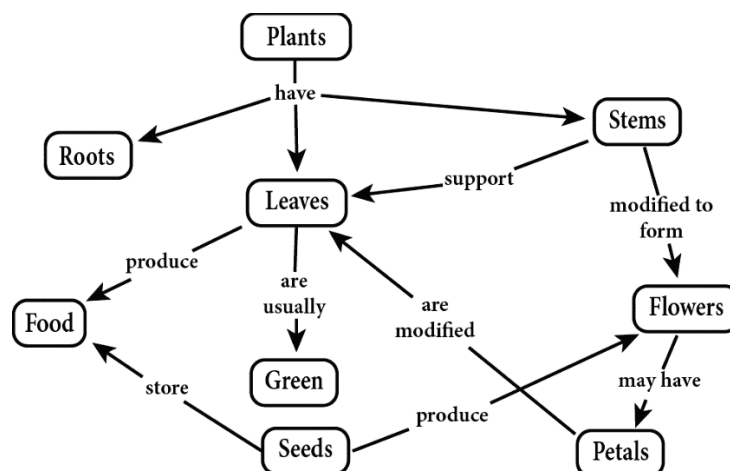


Figure 13. Sample content map depicting connections between biology concepts.

Making a concept-map consists of drawing nodes that represent main ideas and drawing lines between nodes including text to describe how the ideas in the nodes are related. The concept-map assessment represents an alternative method for assessing student learning and comprehension to that of a quiz score, because a concept-map requires a depth of understanding of how ideas are interrelated with little guidance from the assessment itself (Robinson, 1999). Thus, using a concept-map is intended to give insight into deep understanding of content.

Each child was given instructions and the example shown in Figure 13 on how to complete a concept-map, prior to beginning their own concept-map of the ideas contained in the textbook reading. Children were then instructed to “draw a concept-map about what you just read on the paper below. Start out with what you believe to be the main ideas of what you read and connect other ideas from there.” They were given 5 minutes to complete their concept-map and were not allowed to refer back to the text. Each concept-map was analyzed using a rubric based on a standardized rubric used in prior work and scored for accuracy (Radcliffe, Caverly, Peterson & Emmons, 2004; Stoddart, Abrams, Gasper & Canaday, 2000). Concept-maps scores were calculated by summing the number of scientifically accurate connections made. Inter-rater reliability was calculated for 20% of the data and found to be sufficient ($\kappa = 0.83$).

Situational interest. To measure situational interest for the reading session, I included a survey of situational interest with two factors, catch and hold situational interest (see Appendix Table A6 Part I), that is based on a previously validated and reliable measure (Knogler, Harackiewicz, Gegenfurtner & Lewalter, 2015). I modified the language of each item to relate to experiences with reading activities, and in some cases made the reading level of the items more age appropriate. These two factors each included 6 Likert-style items on a scale of 1 (*strongly disagree*) to 7 (*strongly agree*). An example of catch and hold interest items includes: “I think the topics I learned about in the reading activity matter to me.”

Social connection-making. After each session, children completed a survey to measure their perception of the robot along several socially meaningful traits to assess the level of social connection-making the child experienced with the robot. The measures of childrens’ perception of the robot included a survey of 14 items developed from of a measure of social and intelligence evaluations of digital agents that includes five factors: sociable (5 items), mutual liking (2 items), attractiveness (2 items), human-likeness (1 item), and intelligence (4 items; Mutlu, Osman, Forlizzi, Hodgins & Kiesler, 2006; Parise, Kiesler, Sproull & Waters, 1999; See Appendix Table A6 Part III). This survey included 14 adjective pair items where children were asked to rate their feelings about the robot on a scale of 1 (first adjective, e.g., *unhappy*) to 7 (second adjective, e.g., *happy*). For example, one item for the sociable factor asked the child “How bored or excited was your partner?” and the child was asked to choose between bored and excited on the adjective pair scale. Examples of adjective pairs for the other factors on the survey include very little to very much (human-like), not-cute to cute (attractive), not-smart to smart (intelligence). I also asked how much the child liked the robot, and how much the robot liked the child with adjective pairs of very little to very much. I also included one item to assess the child’s feeling of closeness with

the robot based on a previously validated measure (Gachter, Starmer & Tufano, 2015) that found the single item to be equally appropriate for measuring closeness as several other larger measurement tools. This measure asks children to choose one set of increasingly overlapping circles that “best shows your relationship with the robot” (See Appendix Table A6 Part II)

Each survey was scored as a mean score of all items on the survey in order to reduce the scale to a range (1-7) more easily interpreted than a simple raw score. For each survey, I calculated Cronbach’s alpha, with $\alpha > 0.70$ as an indicator of reliability (Crocker & Algina, 2006), and conducted a factor analysis to verify the factor structure of each measure was consistent with models from prior work.

Randomization checks. I also included several measures to estimate whether the randomized groups were relatively equivalent. These measures included the pre-test of content knowledge, reading ability, and self-report Likert-style surveys of individual interest for science (science interest) and individual interest for reading (reading interest). I also asked children to provide demographics including age and gender (See Appendix Table A6 Part IV).

For the reading ability assessment children read a one-page article and answered 6 questions (4 multiple-choice and 2 open-ended) on the article (See Appendix Table A7). The assessment was based on the 5th grade Florida Comprehensive Assessment Test for reading comprehension. Children were given as much time as they needed to read the article, and 5 minutes to answer the questions while referencing the article. Each question was scored on a scale of 0-1 with partial credit for partially correct answers with a maximum possible score of 6.

The science interest and reading interest scales, developed and tested in prior work (see Study 1 and 2 of this work; Michaelis & Mulu, 2017), were based on a previously validated

reliable measure of individual interest (Michaelis & Nathan, 2015; See Appendix Table A1 and A8). The reading interest scale was modified by incorporating language from the Motivation for Reading Questionnaire (Wigfield & Guthrie, 1997). Each of these scales included 10 Likert-style items where children were asked to rate their agreement with each statement on a scale of 1 (*strongly disagree*) to 7 (*strongly agree*). Examples of science and reading interest items include: “if my science homework is interesting, I will keep working at it even if it is difficult,” and “I like to read hard, challenging books.”

Statistical Analysis. As a check of random assignment to condition groups, all group characteristics were compared for mean differences, and a comparison of gender ratios for each group was also considered. To test the hypothesis, I then conducted an independent t-test to compare mean differences between conditions for each of the 10 outcome measures. Since these tests all represented tests of the primary hypothesis, I used a significance test of $\alpha = 0.05$ for each test, without including family-wise error correction as it is unnecessary in this type of testing (Keppel & Wickens, 2004). I do also report the results of significance testing using a Holm-Bonferonni correction for family-wise error rate in the case that the readers would like to apply this more stringent criteria in considering the results. I also consider the effect size for each result using Cohen’s d with conventional effect sizes of small ($d > 0.20$), medium ($d > 0.40$), and large ($d > 0.80$; Cohen, 1988).

Results

All group characteristics were found to be similar between the control and treatment groups (See Table 2), satisfying the randomization check. I also found all survey measures to have high internal reliability and a factor structure similar to prior work. Individual interest in reading ($\alpha = 0.75$; $M = 5.50$; $SD = 0.80$) was higher than individual interest in science ($\alpha =$

0.87; $M = 4.54$; $SD = 1.09$), and both distributions were centered around the mean and similar for both groups ($t(58) = 0.75$, $p = 0.46$). For pre-test assessments, low scores ($M = 3.64$; $SD = 1.70$) indicated that prior knowledge for the physics content was low but similar between groups ($t(58) = 0.62$, $p = 0.53$). Measures of reading ability ($M = 4.36$; $SD = 1.30$) indicated a relatively high reading level that skewed to the left and was even between groups ($t(58) = 1.01$, $p = 0.32$). Both groups also had similar ratios of males to females. Males prior knowledge ($M = 4.07$, $SD = 1.76$) was higher than females ($M = 3.07$, $SD = 1.47$; $t(60) = 2.38$, $p = 0.02$), but no other differences were found between genders. I also found differences in reading ability and prior knowledge were stratified as expected across age. The 12-year old children had higher prior knowledge ($M = 4.72$, $SD = 2.03$) than 10-year-olds ($M = 2.93$, $SD = 1.16$, $p = 0.007$), and 12-year-olds ($M = 5.16$, $SD = 0.46$, $p = 0.0007$) and 11-year-olds ($M = 4.49$, $SD = 1.19$, $p = 0.03$) had higher reading ability than 10-year-olds ($M = 3.59$, $SD = 1.37$). No other main effects were found based on age.

Table 2.

Comparison of group characteristics between control and treatment groups.

Measure	Control	Treatment
	Mean (SD)	Mean (SD)
Age	10.79 (0.62)	11.03 (0.82)
Male/Female	17/12	16/13
Reading Interest	5.40 (0.87)	5.63 (0.75)
Science Interest	4.39 (1.23)	4.61 (1.00)
Reading Ability	4.21 (1.36)	4.54 (1.17)
Pre-test	3.73 (1.56)	3.45 (1.76)

To examine group differences in social connection-making with the robot, I compared measures of children's perceptions of the robot for each group (See Table 3 and Figure 14).

There was a large effect size for differences in closeness, with the treatment group ($M = 3.17$, $SD = 0.89$) significantly higher than the control ($M = 2.41$, $SD = 0.91$, $t(56) = 3.22$, $p = 0.002$, $d = 0.84$). For perception of the robot's sociability, there was a large effect size where those in the treatment group ($M = 5.63$, $SD = 0.98$) had higher mean scores than those in the control group ($M = 4.51$, $SD = 1.11$, $t(56) = 4.09$, $p = 0.0001$, $d = 1.07$). For the measure of mutual-liking, there was a large effect size where the treatment group ($M = 5.53$, $SD = 1.27$) had significantly higher mean scores than the control group ($M = 4.40$, $SD = 1.42$, $t(56) = 3.22$, $p = 0.002$, $d = 0.84$). There was a medium effect for children describing the robot as attractive, with treatment scores ($M = 4.19$, $SD = 1.42$) significantly higher than the control

Table 3.

Perception of robot measures, including Cohen's d measure of effect size.

Measure	Group	M (SD)	t	d	p
Closeness	Control	2.41 (0.91)	3.22	0.84	0.002* †
	Treatment	3.17 (0.89)			
Sociable	Control	4.51 (1.11)	4.09	1.07	0.0001 * †
	Treatment	5.63 (0.98)			
Mutual-Liking	Control	4.40 (1.42)	3.22	0.84	0.002* †
	Treatment	5.53 (1.27)			
Attractive	Control	3.36 (1.46)	2.19	0.57	0.03 *
	Treatment	4.19 (1.42)			
Human	Control	3.45 (1.30)	1.07	0.2	0.29
	Treatment	3.83 (1.39)			
Intelligent	Control	5.83 (1.02)	0.52	0.14	0.60
	Treatment	5.71 (0.72)			

Note: * denotes $\alpha < 0.05$. For all tests, $df = 56$. † is significance using Bonferroni correction

($M = 3.36$, $SD = 1.46$, $t(56) = 2.19$, $p = 0.03$, $d = 0.57$). Finally, no significant differences were found for describing the robot as human-like ($t(56) = 1.07$, $p = 0.29$, $d = 0.20$) or intelligent ($t(56) = 0.52$, $p = 0.60$, $d = 0.14$).

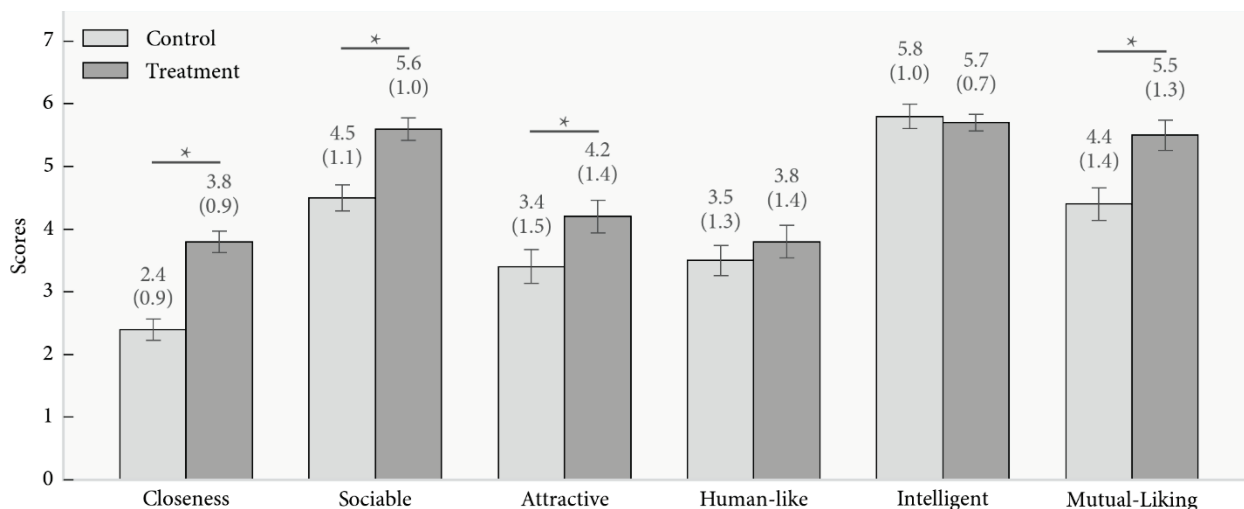


Figure 14. Perception of robot by Condition. Note all scores represent averages of responses on a scale from 1 to 7.

I then compared measures of situational interest and learning for each group (See Table 4 and Figure 15, right). For hold situational interest, there was a medium effect size and significant difference in mean scores, where the treatment group ($M = 5.03$, $SD = 1.27$) was higher than the control group ($M = 4.19$, $SD = 1.49$, $t(56) = 2.3$, $p = 0.03$, $d = 0.60$). For catch situational interest, there was a medium effect size and marginal difference between groups, where the treatment group ($M = 5.00$, $SD = 1.42$) was higher than the control group ($M = 4.21$, $SD = 1.64$, $t(56) = 1.95$, $p = 0.06$, $d = 0.51$). For Post-Test measures (See Figure 15, right), there was no significant difference between control ($M = 5.29$, $SD = 2.16$) and treatment groups ($M = 5.40$, $SD = 2.32$, $t(56) = 0.19$, $p = 0.85$, $d = 0.05$). There was a significant increase in test scores with a large effect size from pre-test to post-test for both control ($t(56) = 3.16$, $p = 0.0025$, $d = 0.83$) and treatment groups ($t(56) = 3.5$, $p = 0.0008$, $d = 0.93$). For scientifically accurate connections made on the concept-map activity (See Figure 15, center), the range of scores was from 0 to 8 and the distribution of scores was strongly skewed to the right with a mean ($M = 2.63$) well above the median ($Median = 2$), and a relatively large standard deviation ($SD = 2.62$). For group differences in scientifically accurate statements on the concept-

map there was a medium effect size where those in the treatment group ($M = 3.48, SD = 2.96$) had significantly higher mean scores than those in the control group ($M = 1.79, SD = 1.95, t(56) = 2.57, p = 0.01, d = 0.67$).

Table 4.

Differences in learning and interest measures, including Cohen's d measure of effect size.

Measure	Group	M (SD)	t	d	p
Concept-map	Control	1.79 (1.95)	2.57	0.67	0.01 *
	Treatment	3.48 (2.96)			
Post-Test	Control	5.29 (2.16)	0.19	0.05	0.85
	Treatment	5.40 (2.32)			
Hold Interest	Control	4.19 (1.49)	2.3	0.60	0.03*
	Treatment	5.03 (1.27)			
Catch Interest	Control	4.21 (1.64)	1.95	0.51	0.06
	Treatment	5.00 (1.42)			

Note: * denotes $\alpha < 0.05$. For all tests, $df = 56$.

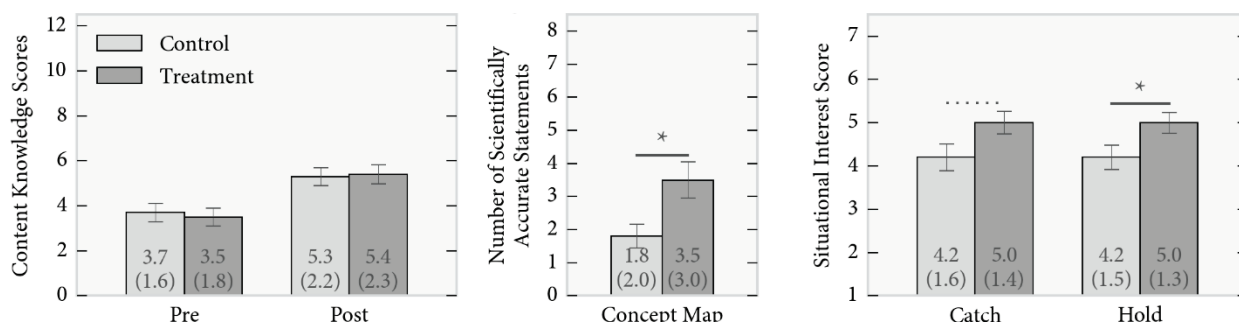


Figure 15. Learning and interest outcome measures with mean score and standard deviation (in parenthesis) including: pre and post content knowledge scores with a maximum score of 12 (left); number of scientifically accurate statements illustrated on a concept map activity with a range of scores from 0 to 8 (center); and catch and hold situational interest scores with a (right). Solid line with * indicates significances at $p < 0.05$, and dotted line indicates significance at $p < 0.10$.

Discussion

In this paper I presented quantitative measures of learning and self-report survey measures of situational interest and social connection-making with the robot in order to test the hypothesis that: Interacting with a socially adept robot will result in greater social connection-making with the robot, situational interest, and learning for children reading a science textbook when compared to a socially neutral robot. I found strong statistical support favoring the socially adept robot for most measures of social connection-making, both measures of situational interest, and for learning as measured by the concept-maps, but no treatment differences on the post-test.

Social connections, interest, and learning. The quantitative measures demonstrate that reading with the socially adept robot supports greater social connection-making with the robot that benefits situational interest and deep learning than the socially neutral robot. These findings are consistent with prior work that suggests socially adept behavior for a robot enhances social connection-making (Leite, Marinho, Pereira & Paiva, 2013), socially supportive behaviors enhance learning and motivation (Saerbeck, Schut, Bartneck & Janse, 2010), and that socially situated interest supports in educational activities benefit interest and learning (Järvelä & Renninger, 2014).

I found evidence that children found the socially adept robot to be more attractive and sociable and that they felt greater levels of closeness and mutual-liking for the socially adept robot. However, I did not find differences in how the children perceived each robot's intelligence or human-likeness. These results are consistent with the design of the study, and with previous work (Leite, Marinho & Paiva, 2013; Lim, Hong, Lee, Suh & Beetz, 2013; Mutlu, Osman, Forlizzi, Hodgins & Kiesler, 2006). I designed the main differences between the robots to be social differences that were driven by verbal and non-verbal social cues. These socially adept

behaviors included head and eye gaze behaviors designed to increase the perception that the robot was making eye contact and averting its gaze in socially appropriate ways, and verbal patterns that included more personal dialogue and more natural and expressive speech patterns. These differences did seem to increase the perception that the robot was sociable and attractive, and may also have contributed to feeling closeness and liking the robot. Interestingly, I did not find differences in how the children perceived the robot's intelligence or its human-likeness. While this finding is in contrast to previous work suggesting non-verbal cues such as proper eye gaze movements increases the perception that the robot is thoughtful (Andrist et al., 2014), it may be that the identical physical design of the robot and input methods contributed more strongly to these perceptions than did any of the social differences between the robots. It also may be the case that children were less aware of the robot's physical movements because they were attending the reading from the textbook. However, these explanations and inferences require further study.

As expected, the differences in social aptitude of the robots led to differences in situational interest, where scores for catch and hold situational interest were higher for children working with the socially adept robot. While the differences in catch situational interest were only marginally significant, I did find a medium effect size, which indicates a fairly strong impact. I believe that liking the robot, feeling closer to the robot, and seeing the robot as sociable and attractive all contributed to the feeling of positive social interaction that improve situational interest (Bergin, 2016, Linnenbrink-Garcia, Patall & Messersmith, 2013). This finding is important, because I am able to demonstrate that social behaviors from the robot contribute to situational interest beyond simple effects from novelty or the learning supports of working with a robot in general. I also find the promotion of hold situational interest is particularly important,

because this type of situational interest is thought to be related to developing lasting individual interest. This outcome supports the feasibility of this type of social robot to promote individual interest development over a long-term interaction, and prior results (Michaelis & Mutlu, 2017) suggest engagement with a similar robot can be maintained over the course of two weeks. What remains to be seen is how well a socially adept robot can maintain those interactions and continue to support interest and learning over an extended period of time while integrated with an authentic curriculum.

Finally, I also found that working with the socially adept robot impacted learning outcomes, but the positive impact on learning was only found from comparison of the concept-map scores rather than the more traditional quiz type of learning measures of the post-test. Both groups had similar mean scores on their post-test quizzes that were significant increases when compared to their pre-test scores. The improvement of test scores for both groups shows augmenting reading a science textbook with an interactive robot with any level of social aptitude may be an effective means for content learning in this context, but further testing is needed to identify if this increase is greater than learning gains from a child reading on their own. The finding of similar post-test scores between groups may be because some of the mechanisms for improved learning through social supports are related to reducing cognitive load during learning via distributing cognitive activity and pointing out relevant information during the learning activity (Hollan, Hutchins & Kirsh, 2000). In the study, robots in both conditions performed these cognitive supporting roles, because the design included controlling for the amount of verbal interaction and the parts of the textbook reading that were referred to by the robot.

Our finding of greater levels of scientifically accurate statements on concept-maps for learners in the socially adept condition may suggest that heightened social connections and

situational interest were more beneficial in an unstructured measure of learning like the concept-map assessment than they are in a traditional post-test quiz. The post-test assessment was designed to assess content knowledge across a variety of levels of difficulty, but the test structure gave students some support for utilizing concepts as these concepts were referred to in other portions of the test. In contrast, the concept-map was an entirely unstructured activity, in which the children were asked to start with a blank paper and recall concepts and organize them according to their connections to each other. This may explain the differences in the measures of learning outcomes, and some of the contradictory results from prior work on the effect of situational interest on learning (Linnenbrink-Garcia, Patall & Messersmith, 2013). However, this relationship requires further exploration.

Conclusion

Increasing individual interest and promoting more robust learning in science are both sorely needed in an age of increasing demand for scientific and technical expertise in the workforce (National Research Council, 2012). I believe the findings provide early evidence that social robots used as learning companions designed to maximize socially adept behaviors and utilize socially situated interest scaffolds help address this problem by improving social connection-making, situational interest and learning in science. Of particular importance, is the relationship between socially adept robot behaviors and increased hold situational interest that contributes to developing individual interest in science. These benefits of working with a social robot, and their ability to perform personalized learning tasks and easily integrate into educational activities may eventually justify the additional cost associated with robotic technology needed to provide this type of social learning support.

For lasting development of individual interest in science, repeated experiences with high levels of *hold situational interest* are crucial (Renninger & Su, 2012), and a learning companion robot appears more capable of inducing this type of situational interest during a science homework reading activity when it utilizes socially adept behavior. Integrating socially adept robot interactions as part of a science curriculum over a series of in-home readings appears to be a feasible way of influencing student interest in science while not disrupting the existing curriculum or homework activity. This recommendation has practical significance for curriculum designers and educators, because it presents a model for designing social robots to be integrated into existing science curriculum, especially in the role of supporting children while reading a textbook for homework.

I also make a significant theoretical contribution to HCI and HRI fields by demonstrating the impact of socially adept robot behaviors on social connection-making, interest, and learning. Social aptitude appears to impact children's perception of the robot as sociable and attractive as well as their feelings of closeness and mutual-like of the robot, but that this aptitude does not necessarily have an impact on how human-like or intelligent the robot appears. This finding is in contrast to other findings in HRI that have found that social behaviors, such as eye gaze aversion while speaking can lead to feeling the robot is more thoughtful (Andrist et al., 2014), and suggests more research in this area is needed to fully flesh out this complicated interaction. I also contribute to theory in interest development and HCI by demonstrating that a robotic agent is effective in playing the role of a social other in interest development, and that the social aptitude of the robot positively impacts the generation of situational interest, including both hold and catch situational interest, in an activity in similar ways to human-human interactions during learning activities. This is an important finding, because it supports the continued exploration of

social robots as learning companions to benefit both learning and interest development in academic content.

Limitations and future work. There are several limitations of the study that need to be addressed in order to strengthen the claims made in the paper and further explore social robots as a learning companion in academic domains. First, while larger than many similar studies of human-robot interaction, the sample size of the study is somewhat low for conducting a randomized controlled experiment and leaves some of the analysis underpowered. I believe the findings, particularly several medium to large effect sizes, are strong indicators of the differences between socially adept versus socially neutral robot behaviors, but future work should increase the sample to bolster the generalizability of these results. A larger sample would also allow inclusion of additional comparison groups to better understand the impact of learning with a social robot. I would suggest future work include additional comparison groups where children read the textbook by themselves or with another technology, such as a tablet computer, so that the learning gains found for both of the robot groups could be better compared against other methods of learning. I would also suggest studies with a larger sample examine the differences in outcomes based on existing interest in science or in reading ability that the study would have been too underpowered to explore. There are also some limitations in interpreting the results of the learning measures. It is not entirely clear why working with the socially adept robot would promote higher concept-map scores but not post-test scores. In this paper, I suggest this may be due to the differences in structure of these assessments and that the concept-map activity may represent a more robust type of learning, but this conclusion requires further validation. This complex result may also be related to the order that these assessments were administered. Each child completed the concept-map before the post-test, and this order may have induced a priming

effect on the post-test scores. Again, further study that balances the order of the learning measures are needed to better interpret the results. There are also limitations to the physical and programming design of the robot that will need to be addressed to better realize the potential of social robots as learning companions, but these limitations are common in this field (Belpaeme et al., 2018). These improvements include better methods of speech recognition for children that would allow for more natural verbal interactions between the child and robot, and methods of expanding a robot's capacity for evaluating and utilizing information about the environment and the learner's social and emotional states.

From a methodological perspective there are two limitations to this study that should be addressed. First, the lab-based study allowed for a comparison of socially adept behaviors to socially neutral behaviors. The socially adept robot has enhanced social *behaviors*, such as making eye-contact and emotional statements, as well as an enhanced *mechanism* to authentically convey those social behaviors, the more natural human-like voice. These enhancements are fundamental improvements to the overall design of the system, but do not allow the precise isolation of social behaviors as the underlying mechanism driving the differences between groups. Therefore, my claims here are limited to describing social aptitude as the cause of the differences in outcomes. Future work should include more studies of comparing social behaviors in isolation to further our understanding of the critical impact of social responses to robot behavior on learning and interest. Second, this study represents successful outcomes for social connection-making, situational interest, and learning, but the interaction with the robot was confined to a controlled laboratory setting during one short reading session. To better understand the impact of socially adept behavior from a learning companion robot that is designed for long-term interaction during homework activity, long-term

in situ testing will be required, which will allow for examination of the stability of the social connections and learning, and the development of individual interest. I intend to address many of these limitations in future work.

In summary, I believe that a learning companion robot is well suited to successfully augment traditional science learning tasks, such as reading informational texts as homework, and that equipping these robots with socially adept behaviors provides additional benefits for social connection-making, situational interest, and learning during a science learning task.

Synthesis of Conclusions Across All Three Studies

Summary of Findings Across Three Studies

There is a growing recognition of the need to expand supports for learners beyond direct cognitive supports, and evidence suggests that providing additional supports for developing interest in the content being learned and for positive social interaction during learning activities are both effective approaches (Bergin, 2016). Designing a personalized learning technology to provide these supports, that I characterize as socially situated interest scaffolds, can be an efficient and effective means for integrating these supports into learning activities. A social robot as the technology platform to deliver these scaffolds affords the greatest potential for social connection making (Wainer, Feil-Seifer, Shell, & Mataric, 2006), which in turn may best support the type of situational interest and deep understanding that lead to lasting individual interest and knowledge (Belpaeme et al., 2018). The goal of this dissertation work is to explore the potential of socially situated interest scaffolding during learning activities with a social robot to improve interest development and learning. The studies examine the robot's capacity to fundamentally

transform learning tasks that have been traditionally isolated and individual (e.g. homework) into a social and interactive activity that can help make significant progress towards this goal.

Evidence from Study 1 suggests that children across all three phases of interest studied had a positive experience with Minnie. They readily made social connections with Minnie and felt the robot could see and understand them. They felt that the robot was a companion in their reading, and could imagine including Minnie in other family and in-home activities in their daily lives. They wanted the robot to be able to also support them in other subjects like math, science, and foreign language learning. For those with maintained situational (phases 2) and emerging individual interest (phase 3), there was an expressed sense of value for the reading activities with Minnie, and those with emerging individual interest (phase 3) also indicated that they felt reading with Minnie would provide supports for increasing reading ability. These results demonstrate that while the robot makes social connections across all phases of interest, the specific aids to interest development are not equally distributed, and expanded personalization and scaffolding capabilities of the robot are needed to address these issues. Overall, the impression children had that the robot was “someone there to read with” was an important finding that laid the foundation for Study 2.

In Study 2, I aimed to examine whether the positive social connections made in Study 1 could be sustained for a longer duration, and whether reading with Minnie could be as effective as participation in a well-designed summer reading activity. Evidence suggests that not only does the robot establish a strong social connection with children, as in Study 1, but that this connection was maintained and deepened over time. Children in both conditions of the study enjoyed their experience, had consistently high levels of situational interest, and sustained their reading activity throughout the two-weeks of the study. Both the robot and paper-based groups

felt the activities helped them improve reading, but while the paper-based control condition attributed this improvement to their additional reading practice, those who read with the robot felt the robot's comments helped them understand what they were reading. It was encouraging to see that the robot could maintain social connection and reading engagement over time, and also important to find that the social connection seemed to deepen over time. This is consistent with theory on establishing long-term interactions with robots (Leite, et al. 2013), and shows how revealing emotions, a personal backstory, and recalling previous interactions all promote long-term engagement that can overcome a potentially drastic reduction in interactions based on the novelty effect, where initial interactions spike from excitement of working with a robot but are not sustained (Leite, Martinho, Pereira, Paiva, 2009). In this study, I demonstrated that a social robot can be designed to augment existing learning activities and to make and strengthen social connections over time.

Having established Minnie's capacity for sustaining situational interest and reading engagement as a reading companion for children, in Study 3 I tested the importance of the social aspects of the socially situated interest scaffolding in making measurable impacts on social connections, interest and understanding. This study examines the importance of socially adept robot behaviors, rather than simply positive effects of *any* robot interaction (due to the novelty effect) and provides key insights into the feasibility of incorporating a learning companion social robot into middle school science curriculum. Findings from this study suggest that there is a measurable impact of the socially adept behavior of the robot. The social version of Minnie, compared to a socially neutral version, promoted situational interest (both catch and hold), deep understanding of the content (based on a concept map activity) and higher levels of social connections with the robot. The higher concept map scores offer a compelling insight into the

type of knowledge, built on deep understanding, that social activity may best promote. This finding is in-line with prior work that suggests that social interaction allows for cognitive loads to be distributed across members of a group, including technological group members (Hollan, Hutchins & Kirsh, 2000), as well as promoting connection-making between the content and prior knowledge and developing new ideas about the content based on conversations and interactions about the subject matter (Miyake & Kirschner, 2015). Perhaps the most important finding from Study 3 is the increased levels of hold situational interest. It is this type of interest support that is thought to lead to developing individual interest (Renninger & Hidi, 2015), and benefits from social interactions (Bergin, 2016). It is encouraging to see that a socially adept robot is capable of playing the social role in learning activities in ways that benefit the process of learning and developing interest.

As robots have become an increasingly viable tool for educational use, it is paramount that we begin to understand how to best harness their social and adaptive powers to positively impact learning experiences, and the work in this dissertation represents significant contributions toward this goal. I have demonstrated across all three studies that children tend to readily make social connections with a learning companion robot designed with socially situated interest scaffolds. These connections begin with a feeling that they are reading with someone else and deepen to include attributing emotions and a personality to the robot. This finding, across all three studies, is important in that it demonstrates how designing for long-term interactions can be effective for understanding, situational interest, and connection making with a robot that can be sustained over time. It is this type of long-term interaction that is needed in order to provide supports to children that can impact their personal or individual interest and knowledge in science and reading.

The studies also demonstrate the utility of describing the supports for interest development as interest scaffolding, by highlighting the varying needs of learners at different phases of interest. Those at lower phases of interest need different supports than those at higher phases, so different supports need to be included for each, and these supports will need to be modified, adapted, and removed over time as the learner's interest develops. The need for socially adept interactions as part of interest scaffolding is also demonstrated by the positive impact on situational interest and understanding that working with the socially adept version of the robot had when compared to a socially neutral robot.

Finally, across the first two studies, children felt that reading with the robot improved their understanding of what they were reading. Some, typically lower interest readers, felt that this was a direct effect of the robot providing some summary or reinforcement of the material they read, and others, typically higher interest, felt reading to the robot helped them focus and take their time, and this provided a better opportunity to understand. This feeling of comprehension support was tested in Study 3, and while there were no differences in pre to post quiz scores, differences in concept map scores provided evidence of higher understanding when reading with the social robot. These findings support the idea that social interaction may be beneficial to both the process of learning and developing interest (Bergin, 2016). Overall, findings from these three studies support the use of a social robot as an effective platform for delivering socially situated interest scaffolding.

Limitations and Future Directions

The findings of these studies are limited by several factors. First, due to the small sample and relatively short duration for all three studies, I am unable to make strong generalizable claims. Future work with a larger sample that extends for months or even years of in-home

evaluation can focus on quantitative data collection for generalizable claims and qualitative assessment of the long-term use of the robot. Results from this type of longitudinal study can inform structural models of the long-term effects and interconnected nature of interest development, learning, and social interaction with a companion robot. Research that allows this longitudinal perspective will also help inform design for maintaining the social connection with the robot, and what interaction patterns seem to improve lasting individual interest and knowledge. Second, all three studies are limited in examining children aged 10–12 during their summer break. This age group is the focus of these studies, because social connections with a robot may peak at this age (Kahn, et al., 2012), but future work should explore other age ranges. Observing child interactions with an educational tool during the summer also limits the findings, because during this time children do not have the usual time constraints of school and thus the interactions may be different during the school year. While the results of Study 3 help establish the impact of socially adept behaviors for learning companion robots, there is also a significant limitation in testing understanding and interest in a lab setting in this study. To better understand the benefits of reading a science textbook with a social robot, further testing should be done in in-home settings, and these tests would further demonstrate ecological validity by having the learning activities integrated into classroom or out-of-school science curriculum for evaluation in an authentic setting.

I also recognize that the interpretations of these findings are influenced by the choice of reading activities and method of delivery of those activities for the control group for Studies 2 and 3. For Study 2, the results indicate that children in the control condition felt that the structure and goal setting aspects of the activities were useful tools to develop reading skill. This indicates that the guided reading activities in the control condition were well received by the children, and

the quality of those activities made them a very competitive baseline against which to compare. In Study 3, the control condition removes the socially adept behavior of the robot, but still uses an animated robot to support learning while reading. In both cases, I chose to include a robust control condition to avoid a “straw man” comparison. For future work, it may be useful to compare the robot with other digital agents, unstructured reading activities or reading a textbook without supports to better characterize the full extent of the robot’s ability to promote understanding and interest while reading. There is also ample room for examining specific effects of robot comments on children’s behaviors (e.g. eye-gaze, attention, reading time), interest development, and learning processes. That is, are there specific types of comments, such as direct summaries or questions posed to the learner, that best guide specific types of learners that might be used to more effectively personalize the learning experience? These studies are limited in examining this question, because most comments were designed to be generally friendly, personal, and informational, but did not have much variation in their style (with the exception of socially neutral comments in Study 3). Framing comments as questions rather than statements or designing for a range of funny and serious, or abstract and concrete comments may be beneficial in certain learning tasks for certain learner characteristics, and the specific benefits of each should be explored. Finally, results of these studies are also limited in the interpretation of measures of situational interest, particularly in Study 3, where I used a survey that asks children to describe their interest in the topic that is inextricably intertwined within the context of reading about that topic with the social robot. Thus, the survey is a measure of situational interest in *reading about physics topics with Minnie*, rather than simply about their interest in reading about physics topics or learning about physics more generally. This introduces a methodological issue in that I make an inference that this type of hold situational interest would apply to interest

in learning about physics, rather than specifically with the robot. To strengthen my claims that the hold situational interest found in Study 3 would lead to increases in individual interest in physics or science, additional measures will be needed in follow up studies. These measures include: survey assessments, including individual interest in science and/or physics (Michaelis & Nathan, 2015a) or other motivational variables such as ability beliefs, expectancies and values (Wigfield & Eccles, 2000); and behavioral measures such as future course choices (Hulleman & Harackiewicz, 2009) and engagement in out-of-school activities (Michaelis & Nathan, 2015b).

I also find that the technical choices made in designing the robot may limit some of its effectiveness during use. That is, for some participants in each of these studies, the experience was diminished by technical challenges inherent to the robotic system. These challenges included errors, such as misread AprilTag codes or accidental shut-downs, and simplified interactions with the robot by using RFID cards (in Studies 1 and 2) or touchscreen buttons (Study 3) or AprilTags as inputs. The technical simplifications and choices made in designing the robot produced a fairly robust system, considering the capacity for extended maintenance-free use in the field, but it is important for future studies to improve the core technology and the interactivity of the social robot platform used. Some of these issues were addressed in the redesign of the robot in Study 3. However, making these improvements over the course of the studies in this dissertation also introduce a further limitation in comparing child interactions with Minnie across all three studies. That is, improvements were made to upgrade the interaction with Minnie, by adding a touchscreen, and to the socially adept voice for Minnie, by implementing the AWS Polli voice. This was an important design development made in response to the feedback from children in Studies 1 and 2, but we cannot directly compare the interactions with Minnie in Study 2 to the interactions in Study 3. Further, we also cannot compare our socially

neutral robot in Study 3 to the paper-based condition in Study 2. Future work should address this limitation by introducing studies with multiple comparison groups to consider whether a socially neutral robot is more beneficial for understanding and interest development than a paper-based or other method of delivering the reading program.

I do also plan to continue to develop and re-design the social robot platform to facilitate a more natural social experience of reading with the robot. Specifically, adding a speech recognition capacity for more natural communication, natural language processing techniques for understanding learning emotional states and intentions, and computer vision techniques, such as optical character recognition, for recognizing book titles and individual pages in the books would make large strides towards this end.

Implications

Given these limitations, I believe that the nine design elements developed during these three studies can be utilized by other researchers and educational technology designers to support interest, ability and knowledge in reading and other educational activities. Study 1 demonstrates an integrated set of design guidelines for a learning companion robot for reading, how these guidelines can be implemented into a social robotic technology, and how children respond socially to the robot. Study 2 shows how an additional design element, incorporating personal and emotional responses that are delivered over time, can help deepen the social connection made with the robot over time, and how the technology can be seamlessly integrated into existing effective learning activities. Findings from Study 3 provide a much-needed efficacy check on the robot's ability to be integrated into a science curriculum to improve educational outcomes while preserving the social connection making capacity of the socially adept robot, and that socially adept behaviors have benefits beyond working with just any robot. Designers and

practitioners can use the guidelines from Studies 1 and 2 as a basis for future companion robot design, particularly for similar learning activity applications, but given the general nature (and cross-disciplinary sources) of the guidelines, they may be effective in other technology learning applications. Teachers and curriculum designers will be able to create lessons that utilize Minnie, or other similar social robots, as reading companions for reading assignments with fiction, non-fiction and academic content books for their students. A teacher may create comments for Minnie that the student can hear while reading at home, or in one-on-one or group activities in the classroom. Parents may also find this learning companion robot technology helpful, particularly for promoting reading interest for children with low to mid-levels of reading interest, or to help maintain interest for those who already have high levels of reading interest.

These findings also contribute to the theoretical understanding of how the experience of working with a social robot can change over time by demonstrating that an initial social connection with a robot can be readily established, deepens over time, and the social actions of a robot positively impact social connection making, situational interest and understanding. As all of these constructs are inter-related, it is important to conduct research that examines them simultaneously, and to bridge theoretical divides in informing future research in this area.

Additional implications of this work are the results from these studies that provide empirical evidence to support theoretically predicted differences in the needs of learners in different phases of interest (Hidi & Renninger, 2006), and the role of social interaction in promoting situational interest and understanding (Bergin, 2016; Pressick-Kilbourn, 2015). In Study 1, children in each phase had distinct responses to what role they felt Minnie would play in their reading activities that were different from other phases. Those in the highest phase expressed interest in expanding the connections with reading materials that they might make

through social interaction with the robot, while those in an emerging individual interest phase focused on their desire for the robot to support their reading comprehension and fluency. Those who did not express a high individual interest in reading felt the robot could support them by helping them find books they would enjoy and to remove some of the boring effects of reading in isolation. These results support interest theory that suggests specific needs of learners are different at different phases of interest and help to further elaborate theory on what these different needs are. This contribution is supported through results from Study 2 that set the stage for describing how a social robot may be effective in improving individual interest over time. Interest development research highlights the importance of repeated experiences that maintain situational interest over time for developing lasting individual interest (Renninger & Hidi, 2015). There is evidence from Study 2 that situational interest in reading activities was supported by both the paper-based and robot reading activities, and that children felt the robot increased their comprehension, motivation and interest in reading over time. However, there was no measured difference in individual interest in reading. This result supports the theory that suggests interest may take months or years to develop into individual interest, and further strengthens the need for longitudinal studies in this area (Renninger & Hidi, 2015). There is also evidence from Study 3 that suggests the social aptitude of the robot does promote hold type situational interest that is believed to be related to developing individual interest, which indicates the importance of social interaction for lasting interest development.

These findings also inform HCI theory and learning sciences theory by suggesting the need for including phases of interest and social interaction as considerations in designing personalized learning technologies, and expand theory in these areas to suggest that a social robot can reduce the boredom of isolated learning activities through social interaction and can

utilize HCI recommended designs for social interaction to support interest and understanding while learning. In this way, I demonstrate how design elements gleaned from HCI theory can be integrated with other theoretical perspectives and implemented to create social connections with children that in turn promote lasting individual interest and knowledge. There is also evidence that increases in understanding as measured by traditional quizzes (Study 3) and reading activity as measured by engagement time (Study 2) do not appear to be influenced by the addition of a robot into the reading activity, or the level of social aptitude of the robot. This suggests that in designing research for educational HCI, it may be necessary to include alternative measures of outcomes such as measures of deep understanding (e.g. a concept map) or qualitative aspects of the reading activity (e.g. post-participation interviews or experience sample measures).

These studies also help to refine HCI theory on sustaining long-term social connections with a companion robot, and provide empirical evidence to support theoretically prescribed suggestions for social robot design to promote engagement and social connections over time. Several examples of prior work were synthesized into the design of the robot in Study 2—including designing for emotional and personal responses that were deliberately added as an important mechanism for sustaining engagement and deepening connections over time (See Figure 2). This work demonstrates that the integration of these elements can be effective for relatively long-term use as reading engagement was sustained over two weeks. I also expand on existing theory by showing how planning a learning activity with a social robot that is based on existing effective learning activities can be a useful method of designing successful HCI and HRI learning environments. That is, reinventing the learning activity for each robot interaction may not be necessary, as the robot interactions can afford support for existing learning structures while also providing crucial social connection-making.

Conclusion

The research in these dissertation studies on learning companion robots required integrating theoretical and methodological elements from HCI, learning sciences and interest development traditions to make a positive impact on theory and practice in each field, and this work demonstrates how cross-disciplinary work can benefit research in each of these areas as well as provide a robust system capable of real-world learning interactions. First, in order to design effective learning technology systems it is valuable to integrate theory from each of these disciplines in a cohesive manner to highlight the processes and mechanisms, mediators and moderators, for learning, interest development and social interaction that are complementary or unique to each field, and to make use of and synthesize prescriptions for design elements that each theoretical tradition provides. Then, assessing the effectiveness of the system to make an impact in real-world scenarios while also demonstrating causal effects of specific design elements requires a multiple and mixed-methods approach, so that the effect can be considered in terms of both ecological and causal validity.

Theoretical integration. The theoretical thread that unites HCI, learning sciences, and interest development traditions in my work is the crucial role of social interaction in all three of these areas. Theory from learning sciences research demonstrates the power of social learning and the distributed cognitive mechanisms that underlay the process of learning. Interest development research emphasizes how social interactions with others strongly influences our choice of activities, value for certain types of activities, connections between our past experiences and value to current activities, and sense of belonging among those who do those activities (Pressick-Kilbourn, 2015; Azevedo, 2013; Deci & Ryan, 2000). These socially induced connections to an activity are strongly bound to the development of interest in that activity

(Bergin, 2016). In HCI research, and particularly human-robot interaction, there is a recognition of a potentially powerful social response to technology where humans reflexively apply social rules and expectations in computer interactions (Nass & Moon, 2000; Duffy, 2003) that can be utilized to enhance interactions with the technology and leveraged to promote desired outcomes of interacting with that technology. In work on learning companion robots, these threads can be woven together by designing social interactions with the learning companion robot that leverage the social responses to the robot to support both improved learning outcomes and interest development. To do so, the social actions of the robot can be designed to make social connections with humans, promote value and belonging within academic topics and provide cognitive social supports for learning. For example, in the reading activities that children engage in with Minnie over these dissertation studies, Minnie slowly reveals her backstory and has personal or emotional responses to the text. This design element is based on prior work in HCI that suggests slowly revealing personal information can enhance long-term interactions with social technologies (Kanda, Sato, Saiwaki, & Ishiguro, 2007). In developing the content of Minnie's backstory and personal responses, I consider ways in which these comments can also promote learning and interest development. So, Minnie can be designed to point out characters in books that are engaging in science, formally or informally, and highlight how those characters are not like stereotypical scientists and are in fact somewhat like the child reading the book. Minnie making a comment like this can now both support social connection making with the robot, while also building a sense of belongingness in science (Pressick-Kilbourn, 2015). Minnie is also designed to recall previous interactions and history with the child as a way of building social connections and long-term interactions (Leite, Martinho & Paiva, 2013). If the types of previous interactions Minnie refers to also reference connections to science content the child is

learning or that the child previously encountered, the robot's comments help support deep understanding and inter-connected knowledge building. In this way, the social interaction design of learning companion robots can be deliberately detailed to serve the purpose of interest development and learning by integrating prescriptive theory from each discipline.

There are of course areas of tension that arise in interweaving multiple research disciplines. One example of this type of tension between the interest development and learning sciences fields is represented by conflicting evidence of the role of seductive or extraneous details in learning texts (Harp & Mayer, 1998). Early in the development of a cognitive theory of multimedia learning (CTML), there was strong evidence that extraneous details, particularly in images, had a negative impact on learning outcomes, because they added unnecessary cognitive load on the learner and this prevented the learner from greatest efficiency in cognitive processing for understanding, making-connections and remembering the key concepts in a learning activity (Mayer, 2005). However, theories of interest and motivation have suggested that this concern was only applicable in a strictly cognitive view of learning, and that by including unrelated but stimulating images, we may increase motivation and activate positive emotions, related to situational interest, that can aid in focus and attention. (Park, Flowerday & Brunken, 2015). This realization has led to newer formulations of the CTML that now recognize the need for attending to affective processes as well as cognitive ones in designing multimedia learning environments, where balancing the two perspectives can lead to greater outcomes than any one alone (Plass & Kaplan, 2016, Moreno & Mayer, 2007).

Relatedly, in work on learning companion robots, there is a tension between the goals of long-term acceptance and use of technologies from an HCI perspective (Lederer, Maupin, Sena, & Zhuang, 2000), and the intentional removal of scaffolding over time from a learning and

developmental perspective (Puntambekar, 2009; Vygotsky, 1978). The goal of a scaffolded learning environment is to support learners during activities that aid in constructing knowledge and building abilities to a level where they no longer need supports to participate fully in those activities. If the primary role of a learning companion robot is to provide these scaffolds, this can become problematic, since removing the scaffold also removes the central actions of the robot. Over time, we might imagine that the robot will simply have nothing left to do. In my framework for designing socially situated interest scaffolds, this may be especially impactful, because the social interactions of the robot are themselves scaffolds that over time should be faded. This problem is only solved if we take a larger ecological view of the role of social robots as companions (Sung, Grinter, & Christensen, 2010). That is, the design of a companion robot needs to consider ways to develop the robot's actions and abilities in concert with the development of the learners it is working with and have utility and application beyond a single learning task. In this dissertation work, the social robot listens to readers while they read and in part provides companionship and aids in motivating reluctant readers to engage in reading. If the robot is effective, the reader will no longer need these specific social supports for reading and will likely begin to prefer to read on their own. This outcome was apparent with some of the higher interest readers in Study 1 of this dissertation.

So, what does the robot do, once it has helped early readers no longer need the social, cognitive, and interest supports that it provides? The robot should be capable of introducing new activities that come with new supports that develop along with the learner. In our example of a middle school child no longer needing social supports for reading, likely to occur before they begin high school, we might imagine the robot now being capable of providing cognitive, social and interest supports for other topics or content areas. At the high school level, these supports

might be useful in science inquiry or foreign language learning – two areas that would be more developmentally appropriate to be verbally interacting with a companion robot. A truly ecological view would also consider what other functions or roles the robot could play as a home companion. In other words, a companion robot is not limited to being a *learning* companion, but should also, ideally, do other companion-like things in the home, that may define its role as more of a personal assistant or entertainer than a peer learner at times. A technology being accepted for long-term use requires the perception that the technology is both useful and easy to use, but the user's perceptions about use can change over time (Venkatesh, Thong, & Xu, 2016). We can use this HCI perspective about the changing needs and perceptions of a user in relation to technology to inform our design for learning and interest, where a broad curricular approach can be taken to designing for interaction with the robot, rather than a short-term perspective on achieving learning or interest goals. We see this naturally occurring in public education, where new levels of complexity are introduced to learners year after year, which entail new types and levels of support. In designing for robot interactions, we can incorporate design considerations that relate the changing needs and perception of the learner as they develop over time. From an HCI perspective, this is likely related to how users perceive the role of companion robots over time (de Graaf, Ben Allouch, & van Dijk, 2018), and from a learning and interest perspective, it is related to their developing level of knowledge and interest in academic activities (National Academies of Sciences, 2018). In short, there is a considerable amount of work to be done to develop theory in educational and learning companion robotics that can account for both how to continually engage the user with the technology while also engaging the user in meaningful learning activities and interest development over a significant duration of time.

Methodological integration. This cross-disciplinary approach also affords the use of methods that explore both ecological validity of the application of a learning companion robot as well as a positivist view on identifying causal effects of variables on measurable outcomes. In turn, these methodological approaches will require innovative, complex, and multifaceted ways of accurately measuring these outcomes. As I highlight in the limitations to Study 3, to advance the impact of this work, there is a need for studies that isolate and precisely control the variables under study, to build fundamental theory, and studies that introduce the intervention into the authentic but messy multivariate real-world settings that the robot might actually inhabit, to inform practical application. This call to both expand and contract the granularity of the methodological perspective demonstrates the fundamental tension between building theory to construct the precise mechanisms involved in designing effective human-robot interactions, to influence learning and developing interest, and studying those mechanisms in real-world environments. Thus, there is a need for research methods that investigate learning companion robots from both an elemental lens, focused on precise components of learning, interest, and HCI, as well as with a systemic lens, that assesses and analyzes learning, interest, and HCI within an entire complex context (Nathan & Sawyer, 2014).

The design-based approach that I take affords theory building while informing practice that Barab and Kapur (2014) describe as “use-inspired basic research” (pg. 152). This perspective is crucial, because both understanding basic mechanisms and processes as well as understanding the socio-cultural context of how and where activities take place are key elements in understanding the true mechanisms of the phenomena of study (Maxwell, 2004). Describing those causal mechanisms within context allows research findings to generalize to a practical level (Barab & Kapur, 2014). That is, findings from a controlled laboratory study, as in Study 3

of this dissertation, can inform and guide real-world application and design, but require further examinations in authentic contexts to validate the practicality of the findings for improving learning, interest development and human-robot interactions. Humans develop interests, knowledge and interactions with technology within contexts and across time (de Graaf, Ben Allouch, & van Dijk, 2018; Azevedo, 2013). However, in Study 3, the precise mechanisms of which aspects of socially adept behavior actually impact learning and interest cannot be identified. To make precise causal claims about these mechanisms will require studies that manipulate small elements of the social behavior of the robot, such as only varying the level of affect incorporated into dialogue, rather than a more omnibus “socially adept” manipulation.

Design-based research in learning companion robots, as a use-inspired basic research approach that investigates phenomena from elemental to systemic granularities of focus, will require multiple measures and mixed methods to fully capture the complex interactions that exist between social interaction with a robot, the development of interest, and learning. There has recently been a call for triangulation of measurements in interest and motivation disciplines that incorporate behavioral observations, self-reports, and biometric measures (Renninger & Hidi, 2011). These types of measures compliment approaches in learning sciences to measure cognitive processes of learning (e.g., Moreno & Mayer, 2007) as well as assessment of learning outcomes such as comprehension and disciplinary practices (Pellegrino, 2013). These multiple measures also are in line with HCI approaches to measure outcomes such as long-term engagement (de Graaf et al., 2016), cognitive processing (Rudmann, McConkie, & Zheng, 2003), and social presence (Mutlu, Osman, Forlizzi, Hodgins & Kiesler, 2006; Parise, Kiesler, Sproull & Waters, 1999). Mixed-methods research can therefore not only be crucial in describing

the phenomena under investigation at levels across context (Onwuegbuzie & Leech, 2009), but also assessing the interactions between social interactions, interest and learning.

Summary. The work in this dissertation demonstrates the potential for social robots, such as Minnie, to augment learning activities with social supports where the benefits of social interaction during learning may not be available or are otherwise lacking. In the studies presented here, reading at home was transformed from an isolated activity into a collaborative experience that can promote comprehension and interest in reading for science learning, and these types of social supports can be applied to learning activities that go beyond reading. The structure of this dissertation, in combining theory, methods and measurement across disciplines and across contexts also serves as an example of conducting research on learning companion robots that informs both theory and practice. I believe that the results of my dissertation work illuminate how we might maximize the benefits that imminent robotic technology can have on society and demonstrate how the integration of social robots into an authentic human activity such as reading can create a transformative educational tool.

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Appendix

Table A1. Four-phase interest development in reading survey. Each item from the survey was designed based on one item, indicated in from the Four-phase interest development in engineering survey (FIDES; Michaelis & Nathan, 2015) with language from the Motivation in Reading Questionnaire (MRQ; Wigfield & Guthrie 1997). The items from previous surveys are indicated in parenthesis.

- 1) I like to read hard, challenging books (MRQ Diff1, FIDES1 PER1)
- 2) If a book is interesting, I will keep reading it even if it is difficult (MRQ Chall2, FIDES2 PER2)
- 3) I read books that are not for school almost every day (MRQ Inv, FIDES3 CE1)
- 4) When I find an interesting book, I'll read it almost every day (MRQ Inv, FIDES4 CE2)
- 5) It is very important to me to be a good reader (MRQ Imp1, FIDES5 Val1)
- 6) I think everyone should try to be a good reader (FIDES6, Val2)
- 7) I like to read books to find out about new things (MRQ Cur5, FIDES7 QUES1)
- 8) When I find something interesting, I like to read books to learn more about it. (MRQ Cur3, FIDES8 QUES2)
- 9) Compared to other students in my class, I am a very good reader (MRQ SE2, FIDES 11 SE1)
- 10) I think that I'm very good at reading books that are interesting to me (FIDES 12 SE2)

Table A2. Initial and post situational interest scales. Items were used to assess student situational interest in the reading activities.

Initial situational interest

- 1) Reading today was very exciting.
- 2) After doing the reading activities, I would like to do more reading today.
- 3) The reading I did today will help me be a better reader.
- 4) To me, reading today was very entertaining.
- 5) I'd like to keep reading the books I started reading today.
- 6) The reading I did today was important to me.

Post situational interest

- 1) Reading the last two weeks was very exciting.
- 2) After doing these reading activities, I would like to do more reading.
- 3) The reading I did the last two weeks will help me be a better reader.
- 4) To me, reading the last two weeks was very entertaining.
- 5) I'd like to keep reading the books I started reading.
- 6) The reading I did the last two weeks was important to me.

ID: 211 Date: _____	Session: 1
A	Last Time Reading I: Read the book titled _____ I read for _____ minutes I ended on page number _____
B	If you need a new book, or would like to switch books, you might like to try one of these three books: 1) Templeton Twins 2) Ramona Quimby: Age 8 3) Boom
C	Today we will set a <u>reading goal of 20 minutes.</u> Don't forget to start the audio recorder while you are reading
D	Daily Reading Log: Book that I read today: _____ I started on page _____ and ended on page _____. I read for _____ minutes. Did you like the book you were reading? ___ Yes ___ No Did you meet your reading goal? ___ Yes ___ No.

Figure A1. Sample page from daily reading packet for paper-based control condition. Each page of the reading packet includes (A) a reading re-cap of the previous days reading, (B) a randomly generated list of recommended books, (C) a reading goal (D), and a reading log for the day.

Table A3. Counts of qualitative codes. Codes are listed by participant and total count (in parenthesis) for pre- and post-interviews.

Theme	Code	Paper		Robot	
		Pre	Post	Pre	Post
Enjoyment	Positive	12 (70)	12 (67)	12 (94)	12 (65)
	Negative	5 (8)	10 (27)	6 (9)	3 (2)
	Neutral	10 (22)	10 (27)	4 (5)	3 (2)
Interest and motivation	Autonomy	2 (4)	2 (5)	2 (2)	1 (1)
	Confidence	2 (2)	1 (1)	2 (3)	2 (2)
	Helpful	1 (1)	4 (6)	0 (0)	2 (1)
	Goals	2 (3)	1 (2)	0 (0)	2 (0)
	Activities motivated to read	6 (13)	4 (12)	2 (3)	7 (9)
	Negative	5 (6)	6 (9)	1 (1)	2 (3)
Reading practice or improvement	Reading skills (combined)	10 (25)	6 (19)	9 (15)	9 (16)
	Fluency	7 (17)	5 (10)	3 (4)	3 (3)
	Comprehension	7 (8)	4 (9)	7 (11)	8 (13)
	Goals	7 (8)	4 (6)	2 (2)	2 (3)
	Negative	0 (0)	2 (2)	0 (0)	1 (0)
	Structure	2 (3)	5 (8)	1 (1)	1 (0)
Anthropomorphism	Perception (Aware or Alive)	NA	NA	12 (31)	8 (27)
	Personality or Emotions	NA	NA	2 (5)	9 (14)
	Physically like a human	NA	NA	11 (36)	6 (15)
Social interaction	Companionship	0 (0)	0 (0)	7 (12)	10 (23)
Technical Issues		NA	1 (1)	NA	8 (13)

Table A4. Qualitative code definitions. Codes that have emerged during open coding, the description of the codes, and the themes that were identified during focused coding.

Theme	Code	Definition
Enjoyment	Positive	Child describes any part of the reading activities in positive terms. Includes the child saying: awesome, best part, cool, excited, fun, good, great, happy, like, love, nice, and any specific sentiment of a positive experience.
	Negative	Child describes any part of the reading activities in negative terms. Includes the child saying: annoying, boring, dislike, distracting, frustrated, OR describes their experiences as being: extra work, felt like work, or hard.
	Neutral	Child describes any part of the reading activities in neutral terms. Includes the child saying: it was okay, no response, not boring, the same as reading without activity, OR when child describes the experience as: didn't mind it, enjoyed, or entertaining.
Interest and motivation	Autonomy	Children described their ability to make their own choices and decision during activities.
	Confidence	Children described improved confidence during reading activities. This includes when a child says: don't feel nervous or felt more confident or less pressure.
	Helpful	Children described the activities as helpful, valuable or useful.
	Goals	Children described the reading goals as a motivating factor to read. Includes the child saying the goals held them accountable, or needed to meet goals.
	Activities motivated to read	Children described the reading activities as a motivating factor to read. Includes the child saying the activities: helped them stay interested in book, made them like reading more, made reading more fun, made them more motivated, read more often, read for more time, read more books, wanted to read more, read a lot of books, read for a long time, or describes experience as interesting.
	Negative	Children described the reading activities as a demotivating factor to read. Includes the child saying the activities: made them want to read less often, read for less time, or were not interesting, not useful, or a waste of time, or were too constraining.
Reading practice or improvement	Fluency	Children described the reading activities as a supporting fluency. Includes child saying: they were a better out-loud reader, improve their fluency, good practice or practice reading out loud, OR describes experience as challenging, that it builds reading habits, or gives a head start.
	Comprehension	Children described the reading activities as a supporting comprehension. Includes child saying: makes me think more, more focused, read more carefully, visualized characters better, improved reading comprehension, improved summary ability, they learned more, or made me think.
	Goals	Children described the reading goals as a way to improve reading. Includes child saying: they made their own reading goals, they meet goals, were more aware of progress, and more aware of time.
	Negative	Children described the reading activities as impeding comprehension or fluency. Includes child saying: it was harder to understand, or harder to understand, or more more difficult to read.
	Structure	Children described the structure of reading activities was a way to improve reading. Includes child saying they were: more organized, put on a schedule, or the experience adds structure.
Anthropomorphism	Perceptive (Aware or Alive)	Child describes the robot as being: awake, knows they are there, knows my name, OR can listen, see, hear, or speak.
	Personality or Emotions	Child describes the robot as having: feelings, personality, insight, intelligence, opinions, or a point of view OR that the robot is funny, interesting, or friendly.
	Physically like a human	Child describes the robots: shape, size, appearance, including: having eyes and the ability to blink, and the ability to move its head.
Social interaction	Companion-ship	Child describe the reading activity as reading to or with a social other. Includes child saying: it was like reading to or with a person, teacher, or group, OR describe a reading companion or friend.
Technical Issues		Child describes some problems in using the reading activities. Includes technical malfunctions, or difficulties, problems, or nuisance of interaction.

Table A5. Pre/post quiz question (Form A).

Pre / Post Questions

Directions: Please answer all the questions below as best as you can. For multiple choice questions, choose all the answers you think are correct.

1. What is a force?
 - A. A push on an object
 - B. A pull on an object
 - C. A push that always makes an object move
 - D. A way to describe the motion of an object
 - E. A way to describe the strength of an object

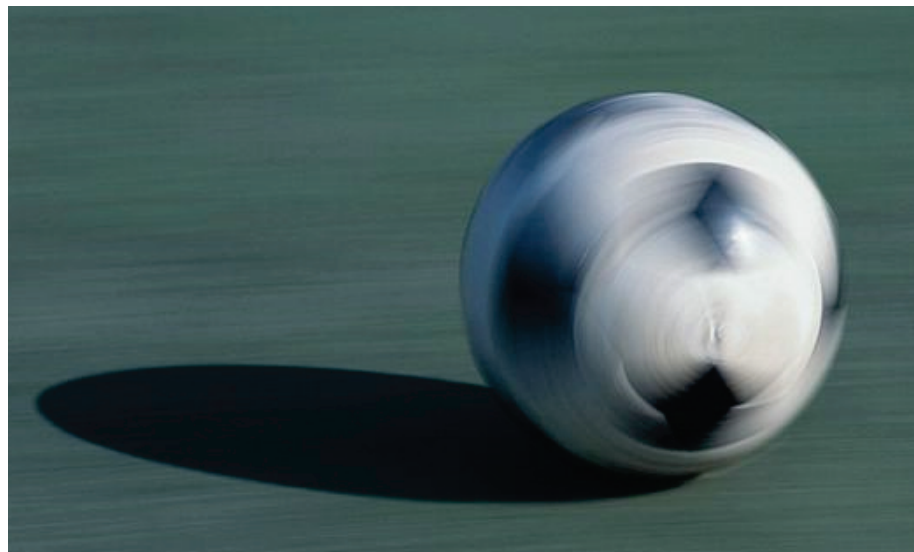
2. Air resistance is:
 - A. A type of fluid friction
 - B. A type of gravity
 - C. A force always in the opposite direction of gravity
 - D. Never equal to the force of gravity
 - E. Always equal to the force of gravity

3. Which force *always* acts opposite to the direction an object is moving?
 - A. Gravitational Force
 - B. Inertial Force
 - C. Force of Friction
 - D. Net Force
 - E. Unbalanced Force

4. Jill tries to push a box of books across the floor. What forces are acting on the box?
 - A. Friction
 - B. Inertia
 - C. Gravity
 - D. Acceleration
 - E. Force from Jill's push

5. Saturn has a much larger mass than the Earth. If you were able to travel to Saturn when you got there your weight would _____ and your mass would _____:
 - A. Increase; Increase
 - B. Decrease; Decrease
 - C. Increase; Stay the same
 - D. Decrease; Stay the same
 - E. Stay the same; Stay the same

11. In the diagram below, the ball is rolling to the right but it is slowing down. Draw arrows to show all the forces that are acting on the ball.



12. Will the forces in number 11 above be balanced, or unbalanced? Explain your answer.

Table A6. Post-study questionnaire. Part I is the pre/post situational interest scale. Part II is the measure of connectedness with the robot. Part III is the survey items measuring social connections with the robot. Part IV are the demographic items.

Part I.

The reading activity today sparked my curiosity.

Strongly Disagree 1 | 2 | 3 | 4 | 5 | 6 | 7 Strongly Agree

The reading activity grabbed my attention.

Strongly Disagree 1 | 2 | 3 | 4 | 5 | 6 | 7 Strongly Agree

I concentrated during the reading activity.

Strongly Disagree 1 | 2 | 3 | 4 | 5 | 6 | 7 Strongly Agree

To me, the reading activity today was very entertaining.

Strongly Disagree 1 | 2 | 3 | 4 | 5 | 6 | 7 Strongly Agree

I had fun during the reading activity.

Strongly Disagree 1 | 2 | 3 | 4 | 5 | 6 | 7 Strongly Agree

The reading activity I did today was exciting.

Strongly Disagree 1 | 2 | 3 | 4 | 5 | 6 | 7 Strongly Agree

I would like to talk about the topics from the reading activity with other people.

Strongly Disagree 1 | 2 | 3 | 4 | 5 | 6 | 7 Strongly Agree

I would like to have more information on the topics from the reading activity.

Strongly Disagree 1 | 2 | 3 | 4 | 5 | 6 | 7 Strongly Agree

I would like to learn more about certain topics from the reading activity.

Strongly Disagree 1 | 2 | 3 | 4 | 5 | 6 | 7 Strongly Agree

I think the topics I learned about in the reading activity are useful for me.

Strongly Disagree 1 | 2 | 3 | 4 | 5 | 6 | 7 Strongly Agree

I think the topics I learned about in the reading activity matter to me.

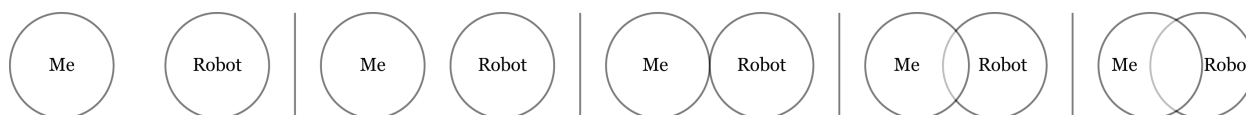
Strongly Disagree 1 | 2 | 3 | 4 | 5 | 6 | 7 Strongly Agree

It is very important to learn about the topics in the reading activity.

Strongly Disagree 1 | 2 | 3 | 4 | 5 | 6 | 7 Strongly Agree

Part II.

Please circle the picture below which best shows your relationship with the robot

**Part III.**

The following part consists of questions about **your opinion of your partner (robot)**. Read each question and mark your answer on a scale from 1 to 7.

How human-like did your partner look?

Very little 1 | 2 | 3 | 4 | 5 | 6 | 7 Very much

How unattractive/attractive was your partner?

Unattractive 1 | 2 | 3 | 4 | 5 | 6 | 7 Attractive

How cute or not cute was your partner?

Not cute 1 | 2 | 3 | 4 | 5 | 6 | 7 Cute

How sad/cheerful did your partner look?

Sad 1 | 2 | 3 | 4 | 5 | 6 | 7 Cheerful

How unfriendly/friendly was your partner?

Unfriendly 1 | 2 | 3 | 4 | 5 | 6 | 7 Friendly

How bored or excited was your partner?

Bored 1 | 2 | 3 | 4 | 5 | 6 | 7 Excited

How shy/outgoing was your partner?

Shy 1 | 2 | 3 | 4 | 5 | 6 | 7 Outgoing

How unhappy/happy was your partner?

Unhappy 1 | 2 | 3 | 4 | 5 | 6 | 7 Happy

How smart or not smart did your partner look?

Not Smart 1 | 2 | 3 | 4 | 5 | 6 | 7 Smart

How irresponsible/responsible?

Irresponsible	1		2		3		4		5		6		7	Responsible
---------------	---	--	---	--	---	--	---	--	---	--	---	--	---	-------------

How unintelligent/intelligent?

Unintelligent	1		2		3		4		5		6		7	Intelligent
---------------	---	--	---	--	---	--	---	--	---	--	---	--	---	-------------

How silly/serious was your partner?

Silly	1		2		3		4		5		6		7	Serious
-------	---	--	---	--	---	--	---	--	---	--	---	--	---	---------

How much did you like your partner?

Very little	1		2		3		4		5		6		7	Very much
-------------	---	--	---	--	---	--	---	--	---	--	---	--	---	-----------

How much did your partner like you?

Very little	1		2		3		4		5		6		7	Very much
-------------	---	--	---	--	---	--	---	--	---	--	---	--	---	-----------

Part IV.

1. Your age? _____

2. Your gender? _____

3. How often do you use a computer?

Never	1		2		3		4		5		6		7	Often (daily)
-------	---	--	---	--	---	--	---	--	---	--	---	--	---	---------------

4. How familiar are you with robots?

Not at all	1		2		3		4		5		6		7	Very familiar
------------	---	--	---	--	---	--	---	--	---	--	---	--	---	---------------

5. How often do you play video games?

Never	1		2		3		4		5		6		7	Often (daily)
-------	---	--	---	--	---	--	---	--	---	--	---	--	---	---------------

6. How often do you read books that are not for school?

Never	1		2		3		4		5		6		7	Often (daily)
-------	---	--	---	--	---	--	---	--	---	--	---	--	---	---------------

7. How many hours did you spent on reading books that are not for school each week? _____

8. How many books have you read in the last 3 months? _____

9. Do you own a robot? No Yes. *What kind?* _____

Table A7. Reading ability assessment.

Directions: To complete the activity, first read the article "The Mystery of the Maya". You can take as much time reading this as you like. When you are done you will answer six review questions on the back of this sheet, and can refer back to the story while you answer. When you finish the reading on this page, STOP, and wait for more instructions.

The Mystery of the Maya

The Mayan Indians lived in Mexico for thousands of years before the Spanish arrived in the 1500s. The Maya were an intelligent, culturally rich people whose achievements were many. They had farms, beautiful palaces, and cities with many buildings. The Mayan people knew a lot about nature and the world around them. This knowledge helped them to live a better life than most people of that time, because they could use it to make their lives more comfortable and rewarding. Knowledge about tools and farming, for instance, made their work easier and more productive.

In ancient Mexico there were many small clearings in the forest. In each clearing was a village with fields of corn, beans, and other crops around it. To clear the land for farms, the Maya cut down trees with stone axes. They planted seeds by digging holes in the ground with pointed sticks. A farmer was able to grow crops that produced food for several people. But not every Maya had to be a farmer. Some were cloth makers, builders, or priests.

The Maya believed in many gods, including rain gods, sun gods, and corn gods. The people built large temples to honor the Mayan gods. Skillful workers built cities around these temples. It was difficult for them to construct these cities, because they had no horses to carry the heavy stone they used to build with. Workers had to carry all of the building materials themselves. Today, many of these ancient Mayan cities and temples are still standing.

Although the cities that the Maya built were beautiful, and the people worked hard to build them, very few of the people lived in them. Usually, only the priests lived in the cities.

The other people lived in small villages in the forests. Their houses were much simpler than the elaborate structures in the cities. They lived in small huts with no windows. The walls were made of poles covered with dried mud, and the roof was made of grass or leaves. Most Maya lived a simple life close to nature.

Measuring time was important to the Maya, so they developed a system for measuring it accurately. Farmers needed to know when to plant and harvest their crops. Mayan priests made a system to keep track of time. They wrote numbers as dots (...) and bars (-). A dot was one and a bar was five.

The Mayan priests studied the Sun, Moon, stars, and planets. They made a calendar from what they learned. The year was divided into 18 months of 20 days each with five days left over. The Mayan calendar was far more accurate than the European calendars of the time.

Around the year 800, the Maya left their villages and beautiful cities, never to return. No one knows why this happened. They may have died from an infectious disease. They may have left

because the soil could no longer grow crops. Archaeologists are still trying to find the lost secrets of the Maya. They are still one of our greatest mysteries.

Reading Review Section

Directions: The questions in this section are based on the story you just read. You may go back to the Reading Section to help you answer the questions. You will have 5 minutes to complete this Activity.

1. The Maya lived in Mexico
 - a. only after the Spanish arrived.
 - b. at the same time as the Spanish.
 - c. only for a few years.
 - d. thousands of years before the Spanish.

2. Many Mayan cities and temples are still standing today because
 - a. they were built from strong materials
 - b. they are not very old.
 - c. they have been rebuilt.
 - d. there is never any bad weather in Mexico.

3. How is the Mayan calendar the same as or different from our current calendar? Use details from the article to support your answer.

4. What is the main idea of this article?
 - a. The Mayan calendar was more accurate than the European calendar.
 - b. The Maya were excellent farmers.
 - c. The Maya were a culturally rich, advanced society.
 - d. The Mayan cities were difficult to build.

5. MOST Maya lived
 - a. in beautiful cities.
 - b. in huts made of poles, mud, and leaves.
 - c. in caves.
 - d. in stone temples.

6. How do we know that the Mayan civilization was an intelligent and cultured one? Use details from the article to support your answer.

Table A8. Science interest scale.

Directions: Please circle one number to indicate how much you agree with each statement. If you strongly agree choose 7 and if you strongly disagree choose 1.

I like to read difficult, challenging books or articles about science

Strongly Disagree 1 | 2 | 3 | 4 | 5 | 6 | 7 Strongly Agree

If my science homework is interesting, I will keep working at it even if it is difficult

Strongly Disagree 1 | 2 | 3 | 4 | 5 | 6 | 7 Strongly Agree

I learn about science or do science activities that are not for school almost every day

Strongly Disagree 1 | 2 | 3 | 4 | 5 | 6 | 7 Strongly Agree

When I find something in science interesting, I always learn more about it.

Strongly Disagree 1 | 2 | 3 | 4 | 5 | 6 | 7 Strongly Agree

It is very important to me to be good at science

Strongly Disagree 1 | 2 | 3 | 4 | 5 | 6 | 7 Strongly Agree

I think everyone should try to be good at science

Strongly Disagree 1 | 2 | 3 | 4 | 5 | 6 | 7 Strongly Agree

I like to find out about new things in science.

Strongly Disagree 1 | 2 | 3 | 4 | 5 | 6 | 7 Strongly Agree

When I find something interesting in science, I like to read books or articles to learn more about it.

Strongly Disagree 1 | 2 | 3 | 4 | 5 | 6 | 7 Strongly Agree

Compared to other students in my class, I am very good at science

Strongly Disagree 1 | 2 | 3 | 4 | 5 | 6 | 7 Strongly Agree

I think that I'm very good at doing science activities that are interesting to me

Strongly Disagree 1 | 2 | 3 | 4 | 5 | 6 | 7 Strongly Agree