HUMAN-ROBOT INTERACTION

Social robots as conversational catalysts: Enhancing long-term human-human interaction at home

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The integration of social robots into family environments raises critical questions about their long-term influence on family interactions. This study explores the potential of social robots as conversational catalysts in human-human dyadic interaction, focusing on enhancing high-quality, reciprocal conversations between parents and children during dialogic coreading activities. With the increasing prevalence of social robots in homes and the recognized importance of parent-child exchanges for children's developmental milestones, this work presents a comprehensive empirical investigation involving more than 70 parent-child dyads over a period of 1 to 2 months. We examined the effects of three robot interaction styles—a passive robot listener, an active robot with a fixed behavior strategy, and an active robot with a strategy-switching mechanism—on parent-child conversational dynamics. Our findings reveal that a robot's active participation enhances the quality of parent-child dialogic conversations. The influence of robot facilitation varied on the basis of parental English proficiency. Strategy-switching robots provided greater benefits to non–native English–speaking families, whereas dyads with native English–speaking parents benefited more from fixed-strategy robots. Overall, this study highlights the promise of social robots that empower parents in fostering their children's dialogic development—a contrast with the prevalent design of educational robots that primarily target children. It provides critical insights into the equitable, nuanced design of long-term family-robot interactions at home, especially in supporting diverse family backgrounds.

INTRODUCTION

As social robots enabled by artificial intelligence (AI) become more common in our homes, concerns are growing about their potential harm to human-human connections (*1*). The responsible design of social robots to purposefully enhance, rather than compromise, human-human interactions and relationships becomes unprecedentedly critical. This study explores the potential of social robots as conversational catalysts in human-group interactions, particularly focusing on enhancing long-term human-human reciprocal interaction at home. We focus on parent-child interactions because of their crucial role in child development.

High-quality, sensitive, and reciprocal caregiver-child interactions critically influence a child's overall development, influencing social, emotional, and cognitive growth (*2*–*5*). Such high-quality interactions are also crucial for young children's language development (*6*–*9*). However, children, especially from low socioeconomic status (SES) families, often experience limited exposure to enriched adult-child conversations. Studies highlight that disparities in the frequency, duration, and richness of conversations between low- and higher-SES families contribute to gaps in vocalization and vocabulary development (*9*–*11*).

The lack of access to parental education and guidance critically contributes to the parental "participation gap"—the disparity in caregivers' active participation in their children's education between low- and higher-SES families (*12*, *13*). As noted by Hoover-Dempsey and Sandler (*14*), well-guided parental involvement is a notable factor in children's cognitive and literacy development, prompting the need for interventions to support it.

Among various interventions targeting the participation gap, traditional home-visiting intervention programs have been shown to be effective, such as (*15*). Yet, accessibility to children's educational resources and extracurricular support is limited in under-resourced communities. Providing home-visiting interventions would be even more limited because of the high costs and the need for specialist facilitators. Given these challenges, there is an urgent need and opportunity to develop interactive technologies that can provide personalized, cost-effective interventions at scale. Although recent developments in educational technology, such as educational apps (*16*, *17*), show promise, few can facilitate real-time, affective, and reciprocal adult-child interaction, such as enhancing parent-child conversations about a story (*18*).

As AI-enabled technology interventions in education become increasingly prevalent, social robots present a promising avenue to foster high-quality parent-child interactions. Exploring the integration of robots in these interactions, particularly their influence on conversational dynamics, is essential. Such interventions could not only address educational challenges but also enrich the variety of interactions between parents and children. To examine the potential of social robots designed for enhancing parent-child conversational interactions, we identified three related subareas: parent-child dialogic interaction, multiperson child-robot interaction, and robot behavior design in the multiperson setting. The state of the art in each subarea, alongside its limitations, is presented in the following three subsections. These three subareas together shed light on both the promising potential and importance of our proposed work and illustrate how our proposed design and evaluation are grounded in prior work while advancing the field.

Parent-child dialogic interaction

Parent-child dialogic interaction, particularly during coreading, is crucial for early childhood development, influencing reading skills, language outcomes, and lifelong reading interest (*19*, *20*). However, the quality of these interactions varies across family contexts, with challenges for non–native English–speaking families. Research shows that bilingual children, especially those with limited English input at home, often lag behind monolingual peers in vocabulary development

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(*21*, *22*). This gap persists from ages 3 to 10, highlighting the long-term influence of the home language environment (*22*). Both home language use and maternal vocabulary knowledge substantially influence children's language development (*23*, *24*).

To enhance parent-child dialogic coreading, educational specialists have introduced protocols to foster meaningful dialogue (*25*–*27*). Coaching techniques, such as the model strategy (*28*, *29*), provide exemplary dialogic reading sessions. Although prerecorded videos offer scalability, they lack personalization. Real-time facilitator coaching provides personalized guidance but is less scalable (*30*, *31*).

To address this trade-off, various technological tools have been developed, including e-book apps (*32*), augmented reality picture books (*33*), and robot companions (*34*). Social robots offer a promising solution, potentially providing real-time, personalized coaching during dialogic coreading sessions. By considering factors such as parental English proficiency, these robotic interventions could address the needs of linguistically diverse families, promoting more equitable outcomes in early childhood language development.

Multiperson child-robot interaction

Although social robots have predominantly been deployed for one-on-one educational interactions with children (*35*), the domain of multiperson child-robot interactions remains relatively underexplored. Existing research in multiperson settings primarily concentrates on interactions among groups of children (*36*–*40*). Such studies have explored roles for robots in mediating conflict resolution among children (*37*) and recognizing social dynamics within groups (*39*).

However, investigations into interactions involving both adults and children are notably more limited (*34*, *36*, *41*). Rudovic *et al.* (*41*) focused on robot-assisted therapy for children with autism, emphasizing the child-robot interaction with less adult participation. Gvirsman *et al.*'s (*36*) Patricc platform showed how robotic facilitation could surpass traditional tablets in triadic interactions but fell short of thoroughly exploring parent-toddler dynamics. The intervention described by Chan *et al.* (*42*), although suggesting benefits such as reduced parental frustration and increased child independence, did not incorporate socially intelligent robots. Chen *et al.* (*34*) designed a teleoperation system to support robot-augmented parent-child story reading, yet the influence on conversation quality needs more investigation.

To our knowledge, the specific influence of robotic facilitation on the conversational dynamics of parent-child interactions has yet to be thoroughly investigated. Our study seeks to fill this gap by elucidating the conversational dynamics within robot-assisted parent-child interactions.

Robot behavior design in multiperson contexts

Social robots have been designed to enhance the dynamics and processes of human groups, such as conflict resolution and participation enhancement (*43*–*45*). Among these prior studies, the robot's support role emerges as a critical design factor influencing the robot's influence on human groups. In multiperson interactions, social robots can assume various roles, ranging from followers to leaders, depending on the level of activity-related support provided. Leader or expert roles involve explicit support, such as coaching or hosting activities (*43*, *46*–*48*). Follower roles support interactions implicitly, displaying vulnerability or emotional expressions (*49*, *50*). Peer-like robots, positioned similarly to humans, can mediate conflicts and promote positive group dynamics (*37*, *51*, *52*). These various roles enable robots to either facilitate effective activity completion or shape group dynamics (*46*, *50*, *52*), potentially providing distinct benefits to individual users and the group as a whole. The robot role design has been conceptualized as target behavior dimensions that a robot could adapt to enhance group experience (*53*).

Another crucial design factor for robot social behavior in multiperson interactions is the communication style. Both verbal and nonverbal behaviors of a robot can substantially influence group dynamics. Verbally active robots can influence trust building (*54*, *55*), group engagement (*56*), psychological safety (*57*), and conversational equality and positivity (*49*). On the nonverbal side, behaviors such as gestures (*58*), gaze (*59*, *60*), navigation (*61*, *62*), and physical orientation (*63*, *64*) also influence group interactions and perceptions. An alternative approach, inspired by Ju and Leifer's theory (*65*) of implicit interactions, involves robots exhibiting implicit nonverbal behaviors as peripheral entities, effectively promoting active participation and collaboration (*44*, *66*).

Recent research has highlighted the potential benefits of enabling robots to dynamically switch between different roles or strategies during interactions. This dynamic approach has proven advantageous in single-person contexts, both in physical cooperation (*67*–*69*) and social interactions (*70*–*72*). In educational settings, role-adaptive robots have enhanced students' motivation in creative dance (*71*), aided learning of computer science concepts (*72*), and promoted learning and affective experiences by leveraging multiple roles (*70*). Although less explored in multiperson scenarios, the concept of dynamic role switching in human-robot interactions shows potential for promoting users' cognitive and affective experiences, such as flow state (*53*).

Overview of our work

Our study aims to integrate robot roles and communication styles into a unified behavior design framework. Motivated by the promising results of emerging behavior-switching paradigms, we examine whether a robot that alternates among six role-style strategies can produce synergistic positive effects on parent-child interactions compared with one that maintains a single strategy. To explore this, we developed social robots capable of engaging in dialogic interactions with parent-child pairs in real home environments (see Fig. 1). Over a period of 1 to 2 months, these robots were deployed in the households of more than 70 parent-child pairs across the United States, with children aged 3 to 7. Our large-scale, real-world empirical investigation focuses on the long-term influence of integrating a robot into home-based parent-child interactions on user conversational behaviors.

RESULTS

Experiment overview

We conducted a between-participant experiment with 71 families, randomly assigned to three conditions: control, fixed-strategy robot, and strategy-switching robot, as illustrated in Fig. 2. Regardless of the experimental condition, each family completed a dialogic reading curriculum consisting of six dialogic interaction sessions and six 4-min instructional videos introducing dialogic concepts. The decision to provide instructional videos to all parents was made to eliminate parental knowledge of dialogic reading as a potential confounding factor. The curriculum was supplemented by prestudy and poststudy parent-child coreading sessions conducted without

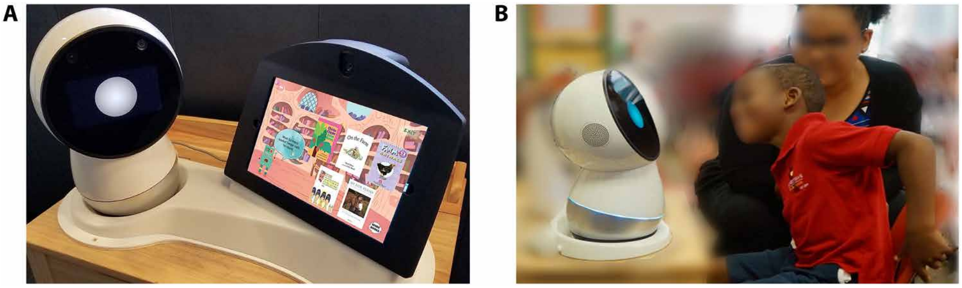


Fig. 1. Home deployment of an integrated robot system. The integrated system consists of two main components: (**A**) the hardware setup including Jibo, Android tablet, and web camera and Intel NUC machine that forms the core interactive system. (**B**) A representative parent-child dyad engaging with the integrated robot system during the 1- to 2-month deployment period, demonstrating the real-world application of the system in home environments.

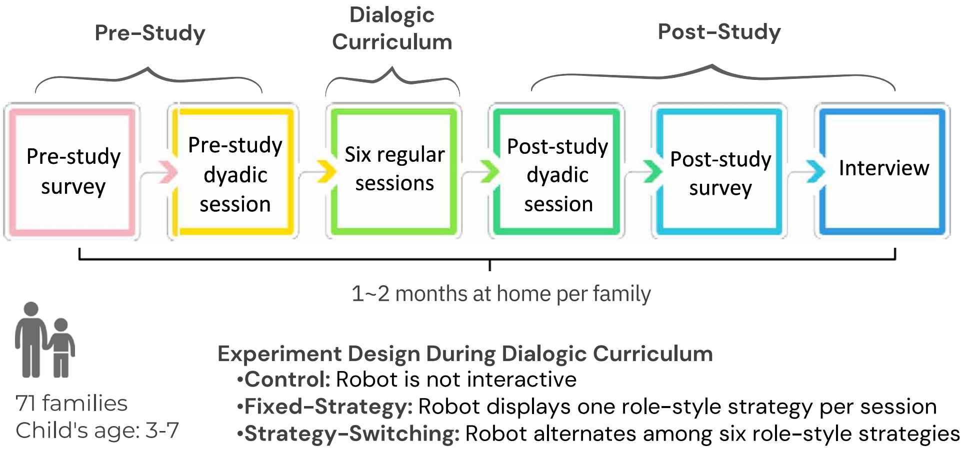


Fig. 2. Experimental design. Study timeline showing pre-/postassessments, six-session dialogic curriculum with robot interaction, and final interview. Three experimental conditions were used for parent-child pairs during the curriculum phase.

the robot's engagement to establish baselines and measure behavioral changes. In the two experimental conditions, families interacted with a robot that actively participated in the dialogic coreading activities. This contrasted with the control group, which included a noninteractive robot serving merely as a listener in the interaction. The difference between the two experimental conditions was that the fixed-strategy robot displayed only one role-style behavior strategy in each session, whereas the strategy-switching robot alternated among six strategies within each session.

Design for active robot participation in parent-child dialogic interaction

In the fixed-strategy and strategy-switching robot conditions, active robot participation incorporated two dimensions of robot behavior: the robot's support role and that of communication style (see Fig. 3 and the "Robot behavior design in multiperson contexts" section). Within the context of parent-child dialogic reading, the three identified support roles for the robot were demonstrator, moderator, and playmate, and the two communication styles were verbal and nonverbal robot intents, as further elaborated in the "Robot interaction design" section and Movie 1.

The demonstrator robot acted as a leading figure who asked high-quality dialogic questions. The moderator robot reminded the parent-child pair to creatively converse about the story. The playmate robot acted as the child's playful peer, mirroring their curiosity and interest in books. An exemplar interaction for each robot role is illustrated in Fig. 4.

When using the nonverbal communication style, the robot relied on nonverbal cues, like eye blinking, to indicate its speaking intent and waited for the parent and child's approval before joining their conversation. In contrast, the verbal communication style allowed the robot to actively and directly join parent-child conversations without indicating its speaking intent and waiting for their approval.

This resulted in six unique robot behavior strategies, such as a verbal demonstrator or nonverbal playmate. Our design aimed to use these role-style strategies to promote parent-child dialogic conversations. The fixed-strategy robot consistently displayed one behavior strategy per session, ensuring that all six strategies were experienced during the six-session dialogic curriculum. In contrast, the strategy-switching robot switched among the six strategies within each session. This strategy-switching mechanism was expected to provide more tailored and engaging interactions, potentially leading to more positive effects on parent-child conversational behaviors compared with a fixed-strategy approach.

Research questions

Our study addresses three main research questions. Our first research question (RQ1) examines how a robot's active participation affects in-the-moment parent-child conversational behaviors during robot-facilitated interaction. This question addresses a common concern that incorporating a robot into parent-child interactions might detract from direct conversational opportunities between the parent and child by dividing the conversational engagement among three parties instead of two. Through a direct comparison of interactions with and without the robot's active participation, we seek to develop a comprehensive understanding of the in-the-moment benefits and drawbacks of integrating a robot into parent-child interactions.

The second research question (RQ2) examines how engaging in a robot-facilitated dialogic curriculum influences parent-child conversational behaviors in their postcurriculum dyadic interaction without the robot's participation. This question evaluates the effectiveness of the robot-facilitated dialogic curriculum in fostering positive changes in parent-child conversational behaviors through long-term at-home robot interactions spanning 1 to 2 months.

The third research question (RQ3) examines how the influence of the robot-facilitated dialogic curriculum on parent-child conversational behaviors varies between dyads with native and non–native speaker parents. This question aims to illuminate the equitable design of long-term robot interactions in parent-child dialogic activities. Considering the pivotal role of parental English proficiency in parent-child dialogic reading, RQ3 examines how social robot design may bridge or enlarge the learning and participation gap among families with diverse backgrounds.

Grounded in the potential of robot interaction in children's conversational and social learning, we hypothesized generally more positive benefits from the two interactive robot conditions compared with the non-interactive robot condition across all three main RQs. Regarding the comparison between the two interactive robot conditions, we hypothesized more positive effects in the strategy-switching robot condition than in the fixed-strategy robot condition, supported by prior empirical findings on the benefits of robot behavior-switching paradigms.

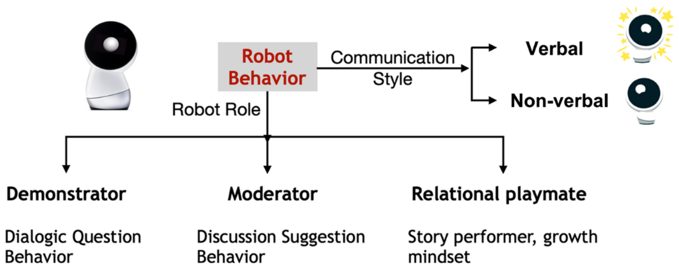
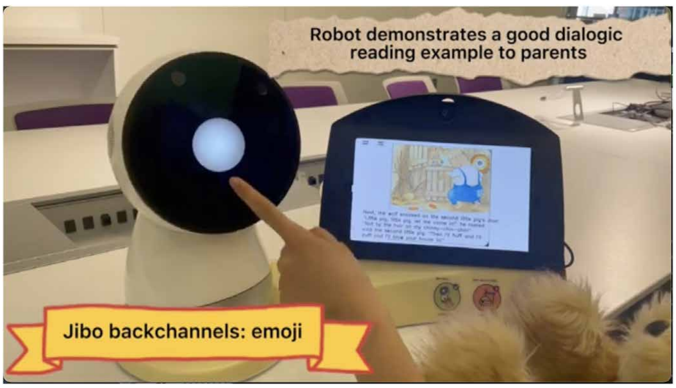


Fig. 3. Robot role-style strategies. Six strategies combining three roles and two communication styles for multiperson interaction.



Movie 1. Robot role-style behavior design in dialogic reading. The integrated robot system dynamically alternates among the roles of demonstrator, moderator, and playmate, using both verbal and nonverbal communication styles during real-time interactive reading sessions with a parent and child.

Overall, the findings in our study revealed three key insights. First, active robot participation enhanced parent-child conversational quality (RQ1). Second, the influence of robot-facilitated interventions varied on the basis of parental language proficiency (RQ2). Third, different robot interaction styles (fixed versus switching) benefited different family profiles (RQ3).

To assess the quality of conversational behaviors between parent and child, six conversational behaviors were operationalized as conversational quality indicators, where higher scores reflected more desirable conversing behavior in parent-child dialogic interaction. These six quality indicators were extracted from the speech of parents and children during real-time coreading sessions, encapsulating the duration and dynamics of conversational patterns for the parent (conv-time-parent and conv-ratio-parent), for the child (conv-time-child and conv-ratio-child), and for the dyad as a group (conv-time-dyad and conv-turns-dyad). To capture the intrapersonal dynamics of a person's conversational interaction, a speaker's conversing ratio was defined as the percentage of a speaker's utterances in conversing relative to their utterances in reading, excluding robot utterances. In addition, three reading-oriented features (read-time-parent, read-time-child, and read-time-dyad) were extracted as supplementary features to provide a more comprehensive view of the parent-child or parent-child-robot dialogic interactions.

RQ1: Robot influence on in-the-moment parent-child conversational behaviors

We first analyzed the conversational dynamics across six sessions of a standard dialogic curriculum under three experimental conditions.

Conversational quality indicators

The Kruskal-Wallis analysis revealed significant differences in two of six conversational quality indicators across the conditions, as shown in Fig. 5. The indicators analyzed were the dyad's total conversing time (conv-time-dyad) and the parent's conversing ratio (conv-ratio-parent).

For conv-time-dyad, the analysis revealed a significant effect of the experimental condition on the total conversing time [$H(2) = 23.90$, $P = 3.88 \times 10^{-5}$], with an effect size of $\varepsilon^2 = 0.32$ and a power of

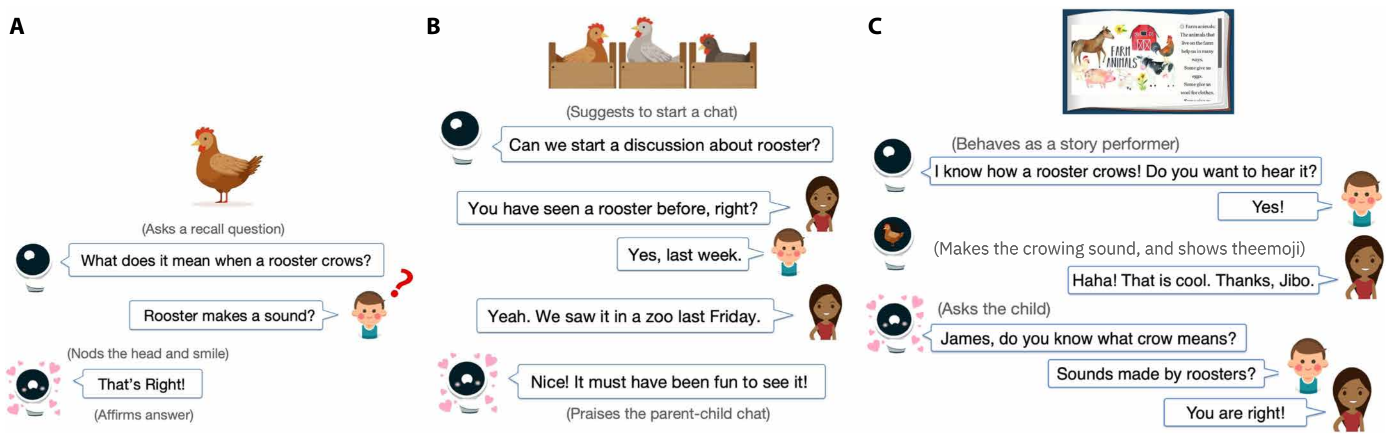


Fig. 4. Robot roles in parent-child interactions. Robot acting in the (**A**) demonstrator role, (**B**) moderator role, and (**C**) playmate role. Each role represents a distinct interaction strategy designed to facilitate different aspects of parent-child dialogic reading.

$1 - \beta > 0.99$. According to Dunn's post hoc test, the control group's total conversing time [mean (M) ± standard deviation (SD) = 34.02 ± 9.08] was significantly lower than those of the fixed-strategy group (M ± SD = 44.11 ± 5.66, $P = 5.31 \times 10^{-4}$) and the strategy-switching group (M ± SD = 45.22 ± 6.72, $P = 1.62 \times 10^{-5}$), with no marked difference between the latter two.

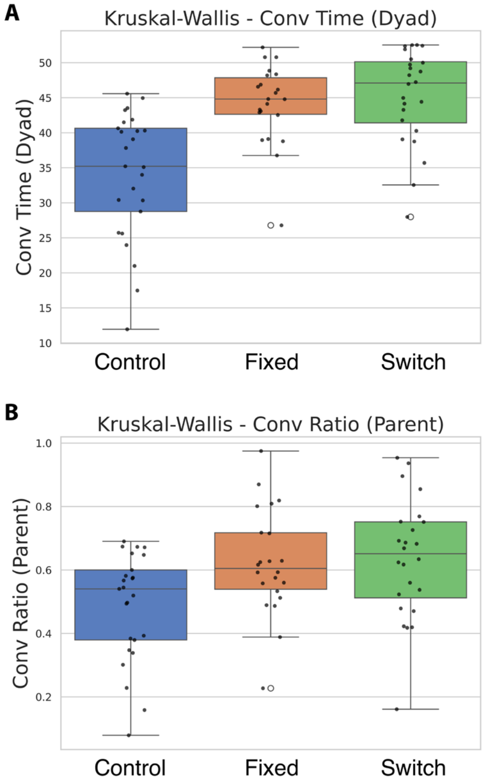


Fig. 5. Influence of robot interaction styles on parent-child conversational patterns. Statistical analysis using Kruskal-Wallis tests revealed significant differences across three robot interaction conditions (control: $N = 25$; fixed-strategy: $N = 22$; strategy-switching: $N = 24$). Box plots show the median, interquartile range (IQR), and data range within 1.5 × IQR, with outliers. (**A**) The dyad's conversational time showed significant variation [$H(2) = 23.90$, $P = 3.88 \times 10^{-5}$], with mean durations of 34.02 ± 9.08 min for the control group, 44.11 ± 5.66 min for the fixed-strategy group, and 45.22 ± 6.72 min for the strategy-switching group. (**B**) The parent's conversational ratio also demonstrated significant differences [$H(2) = 8.67$, $P = 0.039$], with mean ratios of 0.48 ± 0.17 for the control group, 0.61 ± 0.17 for the fixed-strategy condition, and 0.63 ± 0.19 for the strategy-switching condition ($P = 0.02$).

Regarding conv-ratio-parent, the analysis indicated a significant condition effect [$H(2) = 8.67$, $P = 0.039$], an effect size of $\varepsilon^2 = 0.10$, and a power of $1 - \beta = 0.68$. The control condition's mean conversing ratio (M ± SD = 0.48 ± 0.17) was significantly lower than that of the strategy-switching condition (M ± SD = 0.63 ± 0.19, $P = 0.02$), whereas the fixed-strategy condition (M ± SD = 0.62 ± 0.17) showed no significant difference compared to the other two conditions. Overall, a robot's active participation in the parent-child interaction improved the parent-child conversational duration and parent's conversing ratio.

Reading features

The observed increases in conversing time and ratio prompted an examination of three additional reading features to identify which aspects of parent-child dialogic reading were affected by the robot's active engagement. Kruskal-Wallis tests revealed significant differences in both read-time-dyad [$H(2) = 24.05$, $P < 1.10 \times 10^{-5}$, $\varepsilon^2 = 0.32$, and a power of $1 - \beta > 0.99$] and read-time-parent [$H(2) = 23.65$, $P < 1.10 \times 10^{-5}$, $\varepsilon^2 = 0.32$, and a power of $1 - \beta > 0.99$]. Post hoc analyses showed that the control condition had significantly higher reading times for both dyads (M ± SD = 27.07 ± 9.33) and parents (M ± SD = 24.77 ± 9.64) compared with the fixed condition (dyads: M ± SD = 16.46 ± 5.86, $P < 3.29 \times 10^{-4}$; parents: M ± SD = 13.22 ± 5.87, $P < 1.08 \times 10^{-4}$) and the strategy-switching condition (dyads: M ± SD = 15.30 ± 7.21, $P < 2.05 \times 10^{-5}$; parents: M ± SD = 13.40 ± 7.77, $P < 7.00 \times 10^{-5}$). In summary, a robot's active engagement led to a decrease in dyad's reading duration and parent's reading duration in the first 15 min of their dialogic reading interaction.

RQ2: Robot participation and behavioral changes in parent-child conversations

We assessed the influence of robot participation on the changes of parent-child conversational quality in their postcurriculum dialogic interaction without the robot's participation. For each of the six conversational quality indicators, we computed the score differences between the pre- and postcurriculum dyadic dialogic sessions for each parent-child pair.

Table 1 presents the changes in average scores for all six conversational quality indicators from pre- to postcurriculum sessions across all conditions. There was an overall increase in scores for all indicators, except for a −0.95% marginal decrease in the child's conversing ratio (conv-ratio-child) within the control group. Notable

Table 1. Dyad's behavioral change in conversational quality after the dialogic curriculum's completion per condition.

	Condition—score change in mean ± SD (%)		
Quality indicator	**Control**	**Fixed-strategy**	**Strategy-switching**
Conv time (dyad)	8.3 ± 9.8 (38.8%)	5.1 ± 15 (19.2%)	8.0 ± 15 (28.9%)
Conv turn (dyad)	3.3 ± 3.0 (76.6%)	2.4 ± 5.0 (37.4%)	2.1 ± 4.1 (31.1%)
Conv time (parent)	5.4 ± 5.9 (36.8%)	3.6 ± 10.5 (21.7%)	6.5 ± 10.3 (39.3%)
Conv ratio (parent)	0.2 ± 0.2 (56.7%)	0.1 ± 0.3 (17.4%)	0.2 ± 0.3 (47.5%)
Conv time (child)	3.5 ± 4.8 (58.2%)	1.6 ± 6.8 (15.7%)	0.5 ± 10 (4.3%)
Conv ratio (child)	0.0 ± 0.3 (−1.0%)	0.0 ± 0.3 (3.1%)	0.2 ± 0.3 (22.2%)

improvements included a 76.58% increase in the average number of turn-takes per conversation (conv-turns-dyad) in the control condition, 37.40% in the fixed-strategy condition, and 31.12% in the strategy-switching condition. The parent's conversing time (conv-time-parent) also increased significantly, by 36.77% in the control condition, 21.65% in the fixed-strategy condition, and 39.28% in the strategy-switching condition, highlighting a universal enhancement in dyadic conversational quality postcurriculum across all conditions. Kruskal-Wallis tests revealed no significant differences in score changes across conditions for any of the six quality indicators, suggesting consistent improvements regardless of robot participation.

RQ3: Role of parent's English proficiency in robot-facilitated parent-child conversations

This analysis examined the influence of the parent's English proficiency on the effects of robot participation on the parent-child conversational quality, using linear mixed-effects model (LMM) tests for each of the six conversational quality indicators. The results, depicted in Fig. 6, highlighted statistically significant findings for the average number of turns per conversation (conv-turns-dyad) and the parent's conversing ratio (conv-ratio-parent).

For conv-turns-dyad, a significant moderation effect of parent's English proficiency was observed [LR(1) = 8.28, $P = 0.024$] with an effect size of Cohen's $f^2 = 0.13$, indicating that the relationship between robot participation and dyadic conversational turns depended on the parent's English proficiency. Specifically, in the strategy-switching condition, dyads with non–native-speaking parents (M ± SD = 4.34 ± 4.40) exhibited more substantial improvements compared with those with native-speaking parents (M ± SD = 0.62 ± 3.29). Conversely, in the fixed-strategy condition, native-speaking parents (M ± SD = 3.55 ± 5.04) showed more pronounced improvements than non–native speakers (M ± SD = 0.58 ± 4.68). The control condition showed no significant difference, maintaining a consistent gap between dyads with native (M ± SD = 3.51 ± 3.21) and non-native (M ± SD = 2.74 ± 2.28) parents, when compared to the other two active robot participation conditions.

For conv-ratio-parent, significant moderation effects were also detected [LR(1) = 6.11, $P = 0.040$] with an effect size of Cohen's $f^2 = 0.09$, demonstrating that the influence of the robot's participation on the parent's conversing ratio varied on the basis of English proficiency. Non–native-speaking parents (M ± SD = 0.33 ± 0.34) in the strategy-switching condition saw greater enhancements in conversing behavior than native speakers (M ± SD = 0.07 ± 0.29). However, this trend was reversed in the fixed-strategy condition, where native speakers (M ± SD = 0.11 ± 0.27) outperformed non–native speakers (M ± SD = −0.01 ± 0.26). The control condition indicated a slight positive trend for both native (M ± SD = 0.13 ± 0.16) and non–native-speaking (M ± SD = 0.22 ± 0.17) parents.

These significant moderation effects highlighted a consistent pattern: The parent's English proficiency systematically affects the influence of robot participation on parent-child conversational dynamics. When engaged with a fixed-strategy robot, dyads with native-speaking parents benefited more regarding conversational turns and conversing ratios than those with non–native-speaking parents. In contrast, with a strategy-switching robot, the advantage shifts toward dyads with non–native-speaking parents. In the control condition, improvements remained relatively parallel between the two groups.

DISCUSSION

This study explores the influence of an in-home learning companion robot on parent-child conversational dynamics during dialogic interactions. Our findings reveal that active robot involvement increases, rather than reduces, conversational opportunities in parent-child interactions. The dialogic interaction curriculum effectively promotes positive behavioral changes across all conditions. Strategy-switching robots benefit dyads with non–native speaker parents more, whereas fixed-strategy robots show greater benefits for native-speaking dyads.

Overall, we demonstrate that social robots can positively influence parental behaviors, enhancing both child behavior and overall parent-child dynamics. These results emphasize the importance of flexible and diverse robot interaction strategies in ensuring equitable benefits across different family profiles. These findings highlight the importance of parent-focused interventions and equitable, long-term interaction design.

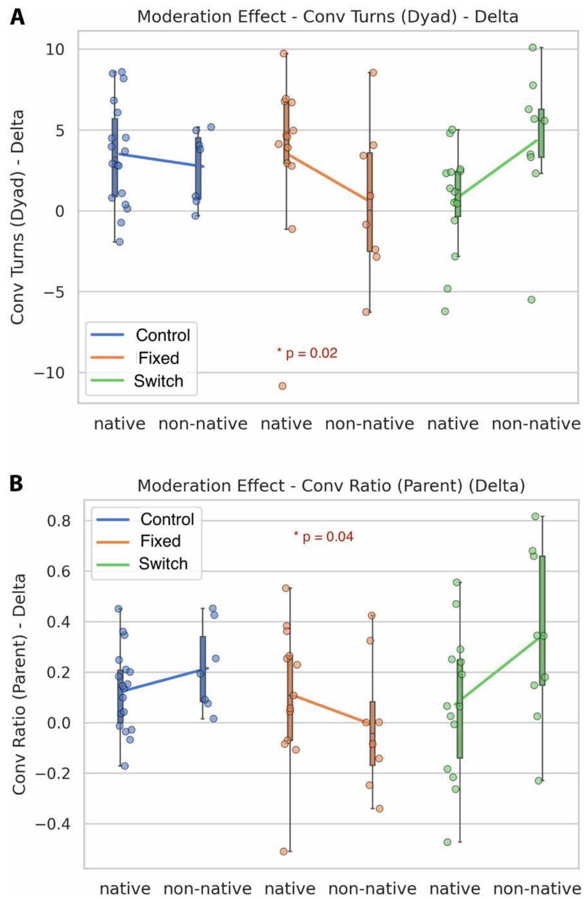


Fig. 6. Influence of parental English proficiency on conversational dynamics. LMM analysis revealed significant moderation effects across conditions (control: $N = 25$, native $N = 18$; fixed-strategy: $N = 22$, native $N = 18$; strategy-switching: $N = 24$, native $N = 18$]. Box plots show the median, interquartile range (IQR), and data range within 1.5 × IQR, with outliers. (**A**) Dyad's average turns per conversation showed significant variation [LR(1) = 8.28, $P = 0.024$], with fixed-strategy robots favoring native speakers and strategy-switching robots benefiting non–native speakers. (**B**) Parents' conversing-to-reading ratio demonstrated similar patterns [LR(1) = 6.11, $P = 0.040$]. The control group showed consistent changes across both language profiles.

RQ1: Enhancing parent-child conversational dynamics through robot interaction

Both active robot types increased dyad's conversing time, with parents showing a notable increase in conversing relative to reading time. This enhancement in conversational behavior was more pronounced among parents than children, with no notable increase observed in the children's conversing behavior when an active robot was present.

Further analysis revealed that dyads engaged less in passive reading during sessions where a robot actively participated in the first 15 min of the activity. The parents, rather than the children, were primarily responsible for this reduction in reading time. It is crucial to note that a decrease in reading time during the initial 15 min does not imply less reading overall; rather, it indicates that reading occurs at a slower pace, allowing for the completion of stories at a rate comparable to that in sessions without robot involvement. These findings address common concerns about the potential for robots to diminish parent-child conversational opportunities. Instead, they demonstrate that robots can enhance the quality of parent-child conversations, suggesting that social robots can be effectively designed to support and enrich parent-child interactions by fostering more active parental involvement in conversation rather than passive reading.

RQ2: Evaluating the long-term influence of robot interaction on parent-child conversational quality

All dyads showed improved conversational dynamics postcurriculum, with increased scores across all quality indicators. This positive influence was observed across all conditions, regardless of the presence or type of robot facilitation during the coreading sessions. Such findings confirms the overall effectiveness of our dialogic reading curriculum consisting of instructional videos and reading sessions in enhancing parent-child conversational quality in their own dyadic interaction even with the absence of the robot's active participation.

There were no notable differences in the magnitude of behavioral improvements among dyads interacting with an active robot versus those without or between dyads engaging with fixed-strategy robots versus strategy-switching robots. This finding can be attributed to the complex interplay of factors unique to individual dyads. These factors, such as language barriers and learning challenges, may have a more notable influence on behavioral improvements than the type of robot participation alone. When analyzing all dyads collectively, without accounting for specific family profiles critical to parent-child conversational interaction, such as parent's language proficiency, these individual-based factors may effectively cancel out and absorb any potential differences in improvements or benefits that dyads might derive from interacting with different robot styles.

RQ3: Improvement variability in parent-child conversational quality based on parental English proficiency

Parental English proficiency notably influenced improvements in conversational quality across conditions, particularly in turn-taking and parental conversing ratios. A consistent pattern emerged from the data, indicating that dyads with non–native-speaking parents derive more benefit from interactions with a strategy-switching robot than those with native-speaking parents. In contrast, native-speaking dyads experienced greater advantages from interactions with a fixed-strategy robot compared with their non–native-speaking counterparts. This observation suggests a reversal in the direction of English proficiency's moderating effect on positive behavioral changes between the strategy-switching and fixed-strategy robot interactions. When dyads did not interact with a robot, the influence on behavioral improvements remained consistent across both native-speaking and non–native-speaking groups, highlighting no notable differences in outcomes. This uniformity further supports the idea that the divergent moderation relationships observed between fixed- and strategy-switching robot conditions may be due to the robots switching their behavior strategies during interactions. When interacting with a fixed-strategy robot, dyads need to adjust to the robot's predetermined patterns, which may be particularly challenging for non–native English–speaking parents. The cognitive load of conversing in a non-native language while adapting to the robot's fixed interactions may amplify these difficulties. Conversely, a strategy-switching robot dynamically adapts to the dyad's real-time behaviors. This accommodation may particularly benefit non–native English–speaking parent-child pairs, potentially explaining the outcome differences between the two interactive robot conditions across user groups.

These findings emphasize the importance of flexibility of the interaction design in robotic systems, especially for non-native parents, who may face challenges with English-centric dialogic reading strategies. For instance, a strategy-switching robot could pose high-quality dialogic questions initially and then shift to a moderating role to encourage more creative conversations. Such strategic flexibility is crucial for supporting learning in dyads facing substantial language barriers, unlike fixed-strategy robots that demand that dyads adapt to a static set of behaviors.

This investigation highlights that although robotic interventions have the potential to enhance conversational dynamics across all dyads, the design and implementation of robot behaviors are critical in determining the extent of behavioral improvements and identifying which population groups benefit the most. Furthermore, it is crucial to recognize that the flexibility of robot interaction styles—such as the ability to switch among diverse behavioral strategies in real time—can substantially influence which user groups and populations derive the most benefit from these interactions. These insights underscore the urgent need for tailored robotic interventions that account for individual differences and demographic profiles in early childhood education and parent-child conversational enhancement.

Empowering parents in parent-child conversations through robot interaction

Traditionally, social agents have primarily targeted one-on-one interactions with children or multiperson interactions focusing on children. However, our research introduces an underexplored paradigm: leveraging the potential of social robots to enhance parent-child interactions. Upon completing the dialogic curriculum, we observed notable improvements in conversational behaviors at both individual (parent and child) and dyadic levels, as shown in RQ2. These enhancements were predominantly driven by changes in the parents' behaviors, underscoring the critical role of parental involvement. Our findings from RQ1 further highlight that a robot's active participation substantially influences parents' conversational behaviors more than children's. In addition, results from RQ3 indicate that a parent's English proficiency critically moderates the extent of positive behavioral changes induced by the robot, affecting both the parent's and the dyad's conversational dynamics.

These analysis results show that the robot's active participation had a more pronounced influence on parents than on children. This outcome is consistent with the dynamics of dialogic coreading activities, where parents, especially those of children aged 3 to 7, typically lead the activity. Given that these children are usually in the early stages of learning to read and are not yet fluent, the parent's role in guiding the interaction is pivotal.

Our study illustrates the potential of designing social robots as effective interventions that enhance parental dialogic behaviors, thereby fostering positive behavioral changes in parent-child interactions. This insight marks a notable shift in the design paradigm for early childhood education robots. Previous research has primarily focused on targeting children directly in the home environment (*73*, *74*), often overlooking the role of parents or relegating them to a secondary position in child-robot interactions. In contrast, our research highlights the importance of focusing on parents in the development of future robotic interventions within parent-child interactions, recognizing their crucial role in a child's development. This perspective paves the way for further research in social robotics within early childhood education, advocating for innovative robot interaction designs and systems that empower parents to actively engage in and enhance their children's at-home learning experiences.

Equitable design considerations in long-term robot interaction

The contrasting relationships observed between a dyad's parental language proficiency and their improved conversational behaviors in strategy-switching versus fixed-strategy robot conditions, as noted in RQ3, highlight the importance of equitable design in long-term social robotic interventions. Our findings with the fixed-strategy robot emphasize that although a robot with a consistent behavior strategy may foster positive behavioral changes across multiple sessions as noted in RQ2, it might disproportionately benefit dyads with fewer learning barriers as noted in RQ3, potentially widening the learning gap between dyads of varying backgrounds.

It is important to clarify that the fixed-strategy robot in our study was not confined to repetitive behaviors. Instead, it demonstrated a diverse array of behaviors, each tailored and contextually relevant to the specific narrative of the story page it interacted with. The term "fixed strategy" refers to the consistent robot role and communication style maintained throughout a session, such as adopting a demonstrator role with a verbal communication style.

In designing robot-facilitated learning interventions, it is crucial to recognize the importance of offering diverse interaction modes and strategies during extended interactions. A robot capable of switching its interaction strategies provides a more flexible and diverse approach that can notably benefit dyads facing greater challenges, such as those with limited English proficiency. By offering flexible, needs-based support, the strategy-switching robots have the potential to bridge, rather than widen, the learning gap among diverse dyads. This flexibility is particularly crucial for ensuring equitable benefits across parent-child dyads, potentially more so in prolonged engagements than in brief encounters.

These insights also stress the need for nuanced robot interaction design and underscore the necessity to evaluate relative benefits across diverse user groups. As we design robot interactions, it is essential to delve into the nuances of individual differences among dyads, uncovering any hidden differential influences beneath the overall positive effects observed on various populations and individuals. Without thoughtful design and user-profile–specific analysis, social robotics technology, although generally beneficial, could inadvertently exacerbate social and learning disparities.

Limitations

Our study has several limitations that should be considered when interpreting the results. First, the pre- and postcurriculum assessments were conducted as single sessions because of resource constraints, which may not fully capture long-term behavioral changes. Future studies should include multiple assessment points over an extended period to provide a more comprehensive understanding of the intervention's influence. Second, our study focused solely on parent-child interactions during structured dialogic reading activities. We did not examine the potential spillover effects on daily conversations outside these sessions. Future research should investigate how robot-facilitated interventions might influence broader family communication patterns. Last, our study was limited to dyadic parent-child interactions and did not consider the broader family ecosystem, including siblings or other caregivers. To fully understand the potential of social robots as conversational catalysts in home environments, future studies should explore their influence on parental interactions with multiple children and their integration into diverse family structures.

Although social robots are now less accessible than other digital tools, our findings on interaction design, strategies, and conversational styles are applicable to diverse platforms, including emerging low-cost options. As the market for affordable social robots grows, our insights can guide the development of more accessible technologies that support family interactions across diverse backgrounds.

MATERIALS AND METHODS

Experiment objective and design

Study protocol

Our between-participant experiment was designed to assess the research questions under three distinct conditions: control, fixed-strategy robot, and strategy-switching robot. The control condition served as a baseline to compare against the two active robot participation conditions. The fixed-strategy robot exemplified a typical design for robot interaction in short-term deployments with brief encounters, where a single behavior strategy guided the robot's actions (such as adopting a specific role like tutor or tutee during the activity). This fixed-strategy condition provided a direct comparison with the strategy-switching robot condition to evaluate whether real-time switching among diverse robot roles and communication styles influenced parent-child conversational dynamics and long-term behavioral changes.

As depicted in Fig. 2, we placed robots in the homes of participant families for a period ranging from 4 to 8 weeks. Each dyad followed a structured schedule that included a precurriculum parent-child dyadic coreading session, six regular sessions as part of the dialogic curriculum, and a concluding postcurriculum dyadic session. Each session typically lasted between 15 and 30 min. All participants received the same robot system and used a tablet mounted on the robot station for reading stories to ensure consistency across the study. During the six designated coreading sessions of the dialogic reading curriculum, the robot interactions varied on the basis of the assigned condition. In the control condition, participants read stories without active robot involvement. In both robot conditions, the robot actively participated in six coreading sessions with parents and children. However, the pre- and postcurriculum dyadic coreading sessions involved only the dyads, with no robot participation.

The study was approved by the Institutional Review Board (IRB) of the Massachusetts Institute of Technology (reference number

1811583321). Each participant's parent signed a form providing consent for both themselves and their child to participate in the study.

Dialogic reading curriculum

Before each dialogic curriculum session, parents in all three conditions were provided access to a 4-min instructional video on effective dialogic reading techniques (see Supplementary Methods). These videos, produced by education specialists from our lab, were designed to introduce parents to foundational dialogic reading practices grounded in the dialogic reading protocols introduced by Whitehurst and Lonigan (*26*), which also guided the robot's interactive design. Each video featured a researcher explaining a specific dialogic reading strategy with practical examples. These videos were emailed to participants before each of the six intervention sessions.

The inclusion of these instructional videos aimed to standardize knowledge about dialogic reading techniques across all groups, thereby isolating the effect of the robot's active participation from potential knowledge gains in the study's outcomes. By ensuring that all participants received the same instructional content, we could more accurately determine whether observed changes in parent-child conversational behaviors were due to the robot's active involvement rather than merely the informational influence similar to that provided by a tablet or phone.

Participants

We recruited 86 US families with children aged 3 to 7 for an at-home study during the 2022–2023 academic year. We took comprehensive steps to ensure a diverse participant pool through targeted recruitment. Each dyad consisted of one parent and one child throughout the study. Out of the initial recruitment, 71 families successfully completed the study, and 15 withdrew for reasons unrelated to robot interaction, as detailed in Supplementary Methods. The final analysis included 25, 22, and 24 families in the control, fixed-strategy, and strategy-switching robot conditions, respectively. Of these, 18, 14, and 14 parents were native English speakers in the control, fixed-strategy, and strategy-switching robot conditions, respectively. Kruskal-Wallis tests confirmed no significant differences in baseline characteristics across conditions.

Integrated robot system

A social robot named Jibo, an Intel Next Unit of Computing machine, an Android tablet, and a web camera set above the tablet made up the integrated robot station (Fig. 1) (*75*). The Android tablet provided an e-book app loaded with more than 20 storybooks recommended by early childhood education experts and teachers. The same app with the same story corpus had been used in prior parent-child dyadic coreading work (*34*, *76*). Dyads had the freedom to select any book from the corpus to read with the robot during a coreading session. This robot system had been tested and evaluated in a prior real-world deployment study that we conducted (*34*).

Our robot system used a balanced approach to autonomy and flexibility in the dialogic interaction activity, designed to minimize confounding effects while ensuring reliable interactions in early childhood education settings. The robot operated with low-level autonomy, responding to easily detectable cues like page turns, and used prewritten, educationally vetted speech scripts for content reliability. This design choice prioritized precision, safety, and responsible deployment over full, flexible autonomy, ensuring that the robot's interactions remained predictable, child-friendly, and free from potential confounds that could affect the study's outcomes.

Robot interaction design

The robot's behavior strategies for both fixed-strategy and strategy-switching conditions were developed along two primary design dimensions, support role and communication style, which were grounded in prior multiperson human-robot interaction research.

Robot roles

We designed three distinct robot support roles to facilitate parent-child dialogic interaction. Overall, the demonstrator focused on the pedagogical aspect, coaching parents on dialogic questioning. The playmate emphasized the social and affective elements. The moderator served as a neutral facilitator, encouraging dialogue without dictating its direction. This placed the moderator role between the pedagogical demonstrator and the social playmate on a continuum. The specific design rationales and the anticipated benefits of the three roles are outlined below.

Drawing from techniques where a human expert provides real-time coaching (*30*, *31*), the demonstrator role involved the robot offering direct instructions and feedback, akin to a tutor tailored to each dyad. This method, rooted in demonstration coaching techniques (*28*, *29*), aimed to enhance parents' question-asking behaviors by modeling positive reading behaviors, such as asking dialogic questions, thereby encouraging parents to adopt these practices in their coreading interactions. It also provided opportunities for dyads to answer high-quality dialogic questions.

When taking on a moderator role, the robot acted as a facilitator that encouraged parent-child pairs to initiate dialogic questions and discussions. By subtly suggesting opportunities for interaction without directly demonstrating, in this role the robot aimed to foster more frequent and diverse parent-child exchanges, enhancing the overall quality of the coreading experience.

A playmate role enabled the robot to adopt a child-like persona and engage in curious and playful interactions, supporting the "learning-by-teaching" approach (*77*–*82*). This role was designed to boost the enjoyment and engagement of both parent and child, promoting deeper story comprehension and vocabulary learning through interactive storytelling and question-asking.

Robot communication styles

We designed two robot communication styles by differentiating between verbal and nonverbal robot intents. The verbal style involved the robot directly participating in the conversation by asking questions or making comments without seeking prior approval, aiming for immediate and proactive engagement with the dyad. The nonverbal style was characterized by the robot's use of nonverbal cues, such as eye contact, body rotation, and leaning forward, to signal its intent to speak without actually verbalizing unless explicitly permitted by the dyad. This style respected the dyad's autonomy, allowing them to choose whether to engage with the robot's contributions.

The fundamental difference between these two styles lay in who initiated the robot-facilitated parent-child conversation: In the verbal style, the robot took the lead, whereas in the nonverbal style, the initiative rested with the dyad. Combining these support roles and communication styles, we designed six unique role-style strategies: verbal-demonstrator, nonverbal-demonstrator, verbal-moderator, nonverbal-moderator, verbal-playmate, and nonverbal-playmate, all enriched with animated speech and nonverbal cues.

Robot's strategy-switching policy

The robot's strategy-switching policy was grounded in the reinforcement learning (RL) framework and built on our prior theoretical work on the conceptual framework for dynamic role switching (*53*) and our empirical work on strategy-switching for children's language learning (*70*). This computational implementation enabled our robot to dynamically alternate among six role-style behavior strategies during real-time interaction. The use of RL to incorporate users' affective and/or cognitive data for adapting robot behaviors had been widely explored in prior work (*70*, *83*, *84*). Following this established approach, we adapted and customized the RL framework to suit the specific needs and contexts of our work.

We implemented our strategy-switching policy using reward machine-based Q-learning (*85*), a particular implementation of the RL framework demonstrated to be effective for agent interaction scenarios consisting of multiple subpolicies. In our case, the Markov decision process encoded short-term interactions, and the reward machine captured long-term cognitive skills and affective moods.

Our robotic system's affective-cognitive perception module continuously monitored the dyad's behavior-based affects, such as facial expressions, and conversational patterns, such as speaker's utterances. Both the affective and dialogic interaction perception submodules were developed or adapted from our previous work (*34*, *86*, *87*). The user affective and dialogic behavior data detected in real time through the perception model were fed into the RL-based strategy-switching policy.

The policy was initially trained in simulation using data from our pilot study (*34*). In real-world deployment, it switched the robot's behavior strategy in response to each group in real time. More details on the strategy-switching policy are provided in Supplementary Methods.

Data collection and feature extraction

Coreading sessions were video and audio recorded using the robot station's integrated camera. Recordings were limited to coreading activities and professionally transcribed. The transcripts included detailed speaker identifications and time stamps for each turn of speech, facilitating a nuanced analysis of each interlocutor's conversational behaviors. The conversational quality indicators were extracted from the transcripts for the parent, the child, and the dyad as a group in each coreading session.

Following the framework suggested by Whitehurst and Lonigan (*26*), we identified three key dimensions of effective parent-child shared reading: dialogic reading, which involves discussions between parent and child alongside story reading; high child participation, which involves substantial portions of child reading and speaking; and active parent-child turn-taking, which involves frequent switching of reading or speaking turns between child and parent. Accordingly, we extracted six conversational quality indicators—two each for the parent, child, and dyad—focusing on both the conversational duration and the dynamics of reading-conversing interactions within each stakeholder. Reading duration for each of the three stakeholders was also extracted as the supplementary reading feature.

Statistical analysis

We assessed distribution normality and variance homogeneity using Shapiro and Levene tests. Kruskal-Wallis tests evaluated differences across experimental conditions for RQ1 and RQ2. In exploring RQ3, we used an LMM to examine the moderation effect of the parent's English proficiency on dyadic behavioral changes. Adjustments for multiple comparisons in our analyses were made using the Benjamini-Hochberg procedure, ensuring the control of the false discovery rate. Results yielding an adjusted P value below 0.05 were deemed statistically significant and are reported accordingly.

Supplementary Materials

The PDF file includes:
Materials and Methods
Tables S1 to S12
Figs. S1 to S4
References (*88*, *89*)

Other Supplementary Material for this manuscript includes the following:
Data files S1 and S2
MDAR Reproducibility Checklist

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