MAPLE: A Multi-Agent, Prosocial Learning Environment, Engaging and Motivating Children

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***Abstract*—Social-robot peers provide new opportunities and benefits for children's education that robot tutors and learning tools cannot. One such opportunity is peer collaboration, which can improve cognitive and affective learning outcomes. We explore this opportunity with a non-humanoid collaborative robot system that we call "MAPLE," a Multi-Agent Prosocial Learning Environment. In MAPLE, our robot, "Maple," physically acts on its environment and coordinates its behaviors with children to complete a task that is both synchronous and collaborative. Findings from a preliminary interaction study involving 17 children suggest that perceived collaboration with a robot can positively influence children's engagement and motivation, particularly in contexts where collaboration is encouraged but not explicitly required. This work offers compelling insights for advancing child-robot collaboration.**

Keywords—child-robot interaction, social robot design, child development, education. empirical studies.

I. INTRODUCTION

Robots have served as tools and tutors for childhood learning, demonstrating a variety of benefits for early education with the potential to increase a child's engagement with educational content. Recent studies in this domain focus on two areas: (a) the development of learning algorithms for robot tutors that are more adaptable to individual children, and (b) a focus on nuanced and flexible robot-peer roles. While more adaptable robot tutors may improve learning outcomes, recent research demonstrates that peers who flexibly alternate between tutor and tutee may improve learning outcomes more than a peer-tutor or tutee without this flexibility [1],[2].

Robot peers and robot collaborators can have flexible roles during interactions so that robot collaborators may improve learning outcomes in similar ways to peer characters. Specifically, collaborators can trigger a variety of collaborative learning mechanisms, e.g., improving motivation as shown in peer-peer contexts [1],[2]. In peer-peer situations, learning outcomes may vary based on how constructive the interactions are within the collaboration

A social robot-collaborator can leverage its flexibility as a peer and also create constructive, collaborative scenarios for children of different ability levels. With peer-peer scenarios, for instance, the constructiveness of a scenario can when two children struggle to work together.. By controlling the level and interactive framework of the robot-collaborator, we can design scenarios that employ collaborative learning mechanisms to enhance individual learning outcomes. Further, robot-collaborators may be accessible to children in times when human peers are not, such as during the COVID-19 pandemic. To ensure the success of these scenarios, it is essential to study collaborative interactions, observing how children engage with a novel agent to achieve shared goals.

Despite the potential benefits of robot-collaborators and an increase of them in education, few studies evaluate the benefits of child-robot, collaborative games. Some studies of collaboration [3] have a passive robot where there is no active collaboration, while other studies focus on turn-taking games. While similar to collaborative scenarios, children perceive turn-taking games differently from simultaneous collaboration and may be less beneficial for children's affective learning outcomes. In response to these shortcomings, our "MAPLE," a "Multi-Agent Prosocial Learning Environment" (Fig. 1), is designed to create active, synchronous, collaboration scenarios. The MAPLE system features "Maple," our non-humanoid, pro-social, mobile robot that physically acts on its environment and coordinates its behaviors with children. While non-humanoid, Maple is designed with affective and communicative behaviors conveyed by its driving patterns and by a continuum-robot "floppy-ear" appendage atop the robot we previously validated [4]. Teleoperation of Maple allows the child-robot collaboration to unfold in a way that reflects peer-peer collaboration and permits us to explore whether a more autonomous child-robot collaborative system is warranted.

Fig. 1. MAPLE, showing two trees, the bridge, pipeline connectors, and our robot, "Maple" featuring a "floppy-ear" that conveys emotions. Not shown are a third tree and the "syrup bucket." (See Fig. 3 for the complete MAPLE).

Our work builds on existing studies of child-robot collaboration by isolating the psychological and behavioral effects of collaboration with an agentic but non-collaborative control group. Our contributions are in creating a framework for collaboration, observing the cognitive and affective

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learning outcomes associated with collaboration, differentiating the psychological effects of collaboration from the effects of real time, synchronous collaboration, and presenting a platform for child-robot collaboration.

II. Robots in Education

Robots are used in education in three main roles: as tools, as tutors, and as peers. Within these categories are different robot embodiments, ranging from humanoid robots (e.g. NAO) to non-humanoid robots (e.g. the snowman-like Keepon and LEGO Mindstorm vehicles). Mubin et al. [5] elaborates on these categories with considerations of their underlying pedagogical theory (Vygotskian or Piagetian), learning domains (metacognition or math), and their environments (classroom or research lab). Our overview will focus on the role of robots – how a robot's role structures these dimensions of robots in education.

A. Robots as Tools

Robots appeared in education in Papert's LOGO Mindstorms featuring a robot turtle for hands-on computational geometry in classrooms. Children interacted with the turtle, linking their movements to geometric concepts, receiving immediate feedback [6]. Papert's constructionist theory posited that learning involves building knowledge through engagement with tools like robot turtles [7].

Robots as interactive tools support the learning of various skills in classrooms. Robots have demonstrated computational thinking, machine learning, and mathematical abilities (e.g., [8]). Beyond technical domains, robots have been shown to enhance creativity, collaboration, piano playing, and storytelling (e.g., [9]). Further, they can aid visually impaired children in exploring geometry, assist autistic children in social skill development [10], and, for all children, encourage creativity and personality exploration [11]. Some studies use robot agents to teach topics; but these robots can inadvertently be perceived as agents, influencing learning interactions [12].

B. Robots as Tutors

Robot tutors serve diverse roles in education, acting as both teachers and peers in settings ranging from individual tutoring to entire classrooms, spanning subjects from language to math [13]. They often outperform computer tablets in terms of learning gains [14] yet fall short of human teachers' effectiveness [15]. Robots can be designed to use verbal and non-verbal cues that engage and motivate children in ways other forms of digital devices cannot [16]; however, excessive social behaviors in robots can sometimes hinder learning [17].

Adaptive to children's behaviors, effective robot tutors maintain focus and challenge children appropriately, using techniques like hidden Markov models, Q-learning, and Bayesian networks [13]. Simple adaptations, such as using a child's name, can also enhance child engagement [18].

Robot tutors excel across various subjects: teaching vocabulary, mathematics, teamwork, and storytelling (e.g., [19]. They can improve learning processes like verbalization and help-seeking strategies, monitor attention, and gauge emotional responses to maintain engagement [19].

C. Robots as Peers

Robot peers can outperform robot tutors in certain situations. For example, in studies comparing robot tutors and peer characters, helping with tangram puzzles, peers increased cognitive and behavioral engagement more [2]. Children focused more on the robot and puzzle, spent more time on the task, and completed more puzzle pieces [2]. Similar benefits were observed when robots switched between peer and tutor roles during tasks, suggesting better learning outcomes with robot peers than tutors [20].

Despite these advantages, only 9% of educational robot studies involve robot-peers [13]. Studies often focus on the "learning by teaching" paradigm where children teach a robot-peer, known as the "protégé effect" [21]. Robots are often designed as younger peers or learners in need of assistance [1]. Some robots initiate interactions by presenting material and then seeking help [22], while others initiate interactions by asking to be taught [23]. Robots that make mistakes before seeking help have been shown to enhance learning, particularly in vocabulary and handwriting skills [23].

Even as passive observers, robot-peers can enhance learning by their presence, simply following along and asking questions. For instance, in a physics learning study, the presence of a robot improved children's willingness to explain responses, prompting deeper engagement than computer tablets [14]. Robots that ask questions and provide prompts during storytelling similarly encouraged children to generate ideas and maintain interest [24].

Additionally, peer-robots can engage children in cooperative and competitive games, which are generally perceived as more enjoyable than solitary activities, though not quite as fulfilling as playing with friends [25].

III. Robots in Collaborative Learning

Collaboration in learning involves multiple agents working together towards a common goal, requiring engagement, interactivity, and synchronous actions [26]. While definitions vary, collaborative tasks typically cannot be completed individually, though there is debate on task and role division among collaborators [26].

Collaboration fosters positive engagements, persistence, coordination, and motivation by establishing shared responsibility [27]. Additionally, collaboration triggers mechanisms like explanation, regulation, and reduced cognitive load, crucial for learning [27]. However, coordination efforts and added cognitive load can sometimes outweigh benefits, particularly in overly simple tasks [28].

Contemporary constructivist approaches to learning and development [36] suggest that collaborative learning benefits both higher- and lower-ability peers through conflict resolution and guided learning [29] . Studies show varied learning gains depending on the social context and peer abilities involved [30].

Social interdependence theory by Johnson & Johnson [28] posits that positive interdependencies motivate collaboration and enhance achievement by aligning individual and group goals. This shared intentionality fosters new insights and higher-level reasoning [28].

In summary, collaborative learning leverages shared goals and interdependencies to enhance engagement and learning outcomes across diverse educational settings.

IV. CHILD-ROBOT COLLABORATION

Most child-robot studies labeled as "collaborative" actually involve *cooperation*, not true collaboration, as they lack synchronous interactions and shared engagement towards a common goal [3]. These interactions often resemble social games where collaboration is optional; that is, they focus on *asynchronous* or *turn-taking* frameworks [1].

Instances of synchronous gameplay are rare and varied. In one instance of synchronous gameplay, Charisi et al. [31] found that voluntary interactions with robots led to better learning outcomes, similar to social games. Similarly, Gordon et al. [22] explored robot curiosity but focused on algorithm evaluation rather than learning outcomes.

Games with complementary roles, like tidying up or maze navigation, show more synchronous elements but lack consistent cognitive or behavioral outcome measures [32].

In our efforts to identify gaps and opportunities in this research space, we prepared a framework for cooperative and collaborative games (Fig. 2) that synthesize the efforts cited here and still other prior work.

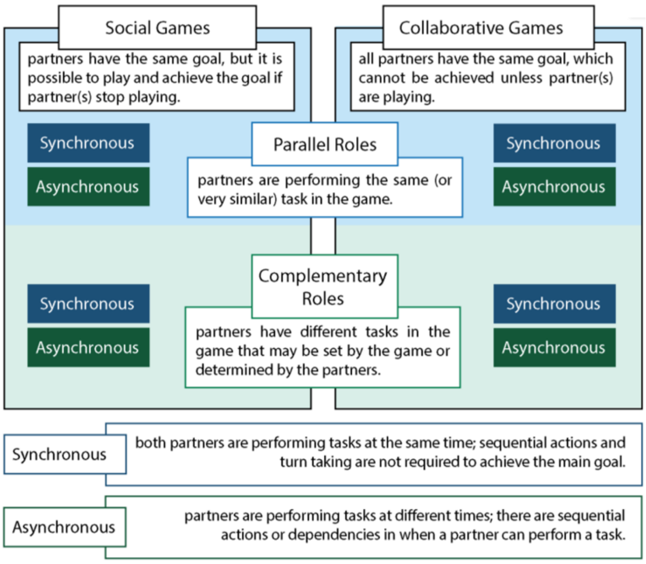

Fig. 2. Our framework for cooperative and collaborative games.

V. OPPORTUNITIES FOR CHILD-ROBOT COLLABORATION

As just considered, few studies involve children and robots in collaborative tasks; most use an asynchronous turn-taking structure rather than synchronous interactions toward a common goal. These studies vary in focus, emphasizing technical outcomes [22], behavioral and affective outcomes [32], or cognitive outcomes [33]. Few still examine both cognitive and affective outcomes [34], making generalization challenging due to diverse task structures.

No study cited here controls for the psychological sense of "togetherness" between children and robots which can enhance a child's motivation on challenging tasks [3]. Studies emphasizing "togetherness" with a robot lack assessment of whether (or not) children perceive "togetherness," and fail to control for this [22]. Few studies involve physical collaboration with a non-humanoid; those that do are rare and focus on competitive tasks or behavioral observations [32].

This mixed research landscape, briefly presented here, suggests ample opportunity to explore the effects of physical collaboration, psychological togetherness, synchronous interactions, and combined cognitive and affective outcomes. Our MAPLE addresses this critical gap by enabling robots to *physically* contribute to tasks in *synchronous*, *collaborative*, social settings with measures assessing psychological togetherness, and cognitive and affective learning outcomes.

VI. MAPLE

The MAPLE system (Fig. 1) is composed of three artificial trees, one syrup bucket, one wooden bridge, thirty connector pieces, and our robot, "Maple." The trees have LED-lit "canopies," "maple syrup spouts that drip LED sap," and "leaves" at the base hiding wiring. Magnets in the connectors enable Maple to pick them up and move them easily. The wooden bridge allows Maple to cross over connected pieces. A selection of components from the system were tested with children at the *Ithaca Science Center*; modifications were made based on observed interactions (Fig. 3).

Fig. 3. Setup at the science center (left); Showing parts of the setup to a child (here, MAPLE's "syrup bucket"); and the final system design (right)

VII. CHILD-MAPLE INTERACTION STUDY

The MAPLE study was designed to answer two main research questions: (1) *Does collaboration with a robot impact children's cognitive and affective learning outcomes?*; and (2) *Do collaborative experiences with a robot influence children's perception of a robot's agency?*. To address these questions, we designed a between-subjects study that varied collaborative language and the robot's collaborative behaviors. Accordingly, the study had two conditions – *Collaborative* and *Non-Collaborative* – and had two main tasks which were referred to as the "connecting task" and the "healing task" (Fig. 4). In the connecting task, children use the connectors to connect the trees to the main bucket. In the healing task, children monitor the trees to make sure they do not get sick (marked by the LEDs turning red), and heal them by pressing on the leaves if they *do* get sick. (Instances from our study can be viewed at https://vimeo.com/980931383.)

Fig. 4. Four Maple behaviors, one in each box above as labelled. Green circles indicate the robot's affective "floppy-ear" appendage behavior.

In the *Collaborative* condition (Fig. 4-top), children are told they will be working together with Maple to accomplish both tasks. In both tasks, Maple's behaviors attempt to replicate a helpful and engaged peer: Maple attempts to engage with the child during the tasks with motions and affective fin behaviors. In the connecting task (a parallel or complementary role, social game), working with Maple is optional but in any case Maple seeks out connectors and brings them to the child without being asked. In the *Healing* phase (parallel role, collaborative game), children are told that to heal a tree they need to press on one of the leaves and Maple needs to press on another. In this healing task, children are required to work with Maple to accomplish their goal of healing the tree(s). For both tasks, Maple responds with a "happy" motion of its "floppy-ear" appendage (see Fig. 1) whenever the child says something positive to Maple, does something for Maple, or something positive happens with the task (like successfully healing a tree). When Maple is unable to do something (such as its path being blocked by connectors), Maple makes a "sad" motion with its floppy ear.

In the *Non-Collaborative* condition (Fig. 4-bottom), children are reminded of the things Maple is able and unable to do (such as follow directions), but no collaborative language is used. Maple does not attempt to engage with the child, but appears to be just as "busy" as it is during the collaborative condition. To replicate the affective actions in the *Collaborative condition*, Maple moves its "floppy-ear" in either a happy or sad motion when it reaches the corners of the room, but not in response to a child's engagement or task completion. During the connecting phase, Maple will retrieve a connector initially, but then carry it around the perimeter of the room. Maple will not bring it to the child unless directly asked, but is also unable to stop a child from retrieving it if the child chooses. Maple will respond to any instruction from the child in the same patterns as the *Collaborative* condition, but does not initiate engagement. During the healing task in the *Non-Collaborative* condition, children are told they can heal the tree by putting their hands on two different leaves; there is no need for them to engage with Maple; instead, Maple follows the same perimeter tracing pattern as the first task with affective responses in the corners. While Maple does not collaborate with children in this condition, Maple otherwise conveys the same agency cues and participates in the same affective behaviors.

A total of 17 children between ages five and seven participated in the study. IRB approved our protocol and caregivers gave consent for their child to participate. One child was excluded from the analysis due to observing the experimenter controlling Maple. Data was not collected on one other child who did not consent to video recording.

The study was led by two research team members: one who led the child through the task, and one who controlled Maple from a separate room. Maple was teleoperated for the duration of the study. Prior to beginning the task, children were introduced to the different elements in the space and to Maple. Maple demonstrated its capabilities with participation of a research team member who interacted with Maple in a positive and friendly manner. Children were then given instructions on the first task (*Connecting*) and told they can let the researcher know when they are ready to move on; at this point, the researcher returned to the room and instructed them on the second task (*Healing*).

A. Dependent Variables and Measures

Observed measures include cognitive and affective outcomes. The primary cognitive measure was an open-ended question about making maple syrup, which was coded for recall about different elements of the maple syrup tasks. Secondary cognitive measures focused on observational learning about Maple's capabilities. Affective measures included persistence, motivation, and engagement. Persistence was measured as time on task and task completion, while motivation was measured with smiley-o-meter scale questions adapted from the *Intrinsic Motivation Inventory*.

Engagement was coded through the *datavyu* video coding software and was broken into two categories: social collaboration and explicit coordination [26]. Explicit coordination could be verbal or non-verbal but was designed to control Maple. Social collaboration consists of those behaviors that focus on coordinating actions and maintaining a positive relationship with Maple. The full breakdown of coded behaviors is shown in Table I.

TABLE I. ENGAGEMENT CODING CHART

Engagement Type	Behavior	Description or Example
Explicit Coord.	Verbal Command (VC)	A verbalization for Maple to follow (immediate)
Explicit Coord.	Directive Gesture (DG)	A clear nonverbal action for Maple to follow
Social Collab.	Verbal Encouragement (VE)	Praise or polite utterances towards Maple
Social Collab.	Physical Encouragement (PE)	Positive physical interactions like petting
Social Collab.	Facilitative Gestures (FG)	Physical actions that help Maple on the task
Social Collab.	Informative Gestures (IG)	Non-directive gestures that provide information
Social Collab.	Cooperative Communication (CC)	Status or progress updates, Joint ("We") language

In addition to these measures, we measured Maple's agency with emotional, mental, biological, and moral questions [35]. Perceived agency was important to measure as it can influence children's willingness to trust and help a robot [35] and, by extension, to collaborate with a robot. Other measures include manipulation checks, task difficulty, and means and level of communication with Maple.

VIII. Results

Final analysis was conducted as a 2x2 design between condition and perception of collaboration, since this perception did not always line up with the condition. The *Collaborative* condition was more likely to be perceived as collaborative, with only one child (12.5%) not perceiving collaboration. The *Non-Collaborative* condition result was divided (50% perceived collaboration, 50% not).

Total agency scores showed no significant differences by condition or perception of collaboration, which demonstrates that both conditions were agentic and that collaboration did not impact perceived agency. When considering Maple's character, none of the children viewed Maple as a teacher but did report Maple as a friend, sibling, pet, peer, and RC toy, suggesting that Maple was defined appropriately as a peer character and not a teacher. Persistence measures (time on task and task completion) showed no significant main effects by condition or perception of condition. There was a significant interaction ($p = 0.021$), but this is based on the contrast in the *Collaborative* condition, where the only child who did not perceive collaboration also did not connect any trees; further study would be needed to confirm this interaction. On average, time on task was higher for the first task (*Connecting*) than the second task (*Healing*) (MT1 = 13.28, MT2. = 7.37) The average number of trees connected was 1.62, and the average number of trees healed was 7.36.

Motivation showed no significant main effects or interactions, but the effect of perceived collaboration approaches significance ($p = 0.13$), with children who perceived collaboration being more motivated than children who did not ($M_{PC} = 3.55$, $SD = 0.64$, $M_{PNC} = 2.80$, $SD = 0.97$). While the observed effect size is large, there was a wide confidence interval (Cohen's $d = 0.91$, $CI = [-0.37, 2.13]$).

TABLE II. MOTIVATION MEASURES BY GROUP (MAXIMUM SCORE: 4)

Condition	Perceived Condition	Motivation (Median)	Motivation (Mean)	SD
Collab	Non-Collab	2.5	2.50	NA
Collab	Collab	4.0	3.50	0.76
Non-Collab	Non-Collab	3.0	2.88	1.11
Non-Collab	Collab	3.5	3.67	0.29

Engagement varied by condition and by engagement type see Fig. 5). Total engagement was highest for the child who was in the *Collaborative* condition but did not perceive collaboration ($M_{C\text{-}PNC} = 105.00$, $SD_{C\text{-}PNC} = NA$), possibly because they were continuously directing and thanking the robot. The least engagement was seen in the *Non-Collaborative* condition that did not perceive collaboration ($M_{NC\text{-}PNC} = 5.667$, $SD_{NC\text{-}PNC} = 8.083$). There were no significant main effects or interactions for total engagement, but there was a significant contrast in the *Non-Collaborative* condition between the children who perceived collaboration and those who did not. For this condition, perceived collaboration increased engagement.

Explicit coordination showed no significant main effects or interactions by condition or perception, but the interaction was approaching significance ($p = 0.105$). For the *Collaborative* condition, explicit coordination increased when children did not perceive collaboration, while the opposite was true for the *Non-Collaborative* condition. For social collaboration, the main effect of condition was approaching significance ($p = 0.07$, $M_C = 25.75$, $SD_C = 19.44$, $M_{NC} = 5.43$, $SD_{NC} = 5.53$). Thus, when Maple initiates engagement, children are more likely to behave in ways that support a positive relationship with Maple by helping, encouraging, and informing. In contrast, when Maple is not initiating engagement and children feel they are not collaborating with Maple, they rarely engage at all.

Children did, however, demonstrate all of the defined engagement behaviors (Table I). Children engaged in all of the specified engagement types, though patterns of engagement varied by condition and perception of collaboration. In general, verbal commands were more common than directive gestures, and verbal encouragement was the most common type of collaboration. These trends change when we look at individual tasks where collaboration was optional or required. For the first task, children in the *Collaborative* condition engaged more, with the most engagement occurring where the child did not perceive collaboration. In this case, explicit coordination is almost twice as great as social collaboration. In the first task, verbal encouragement was the most common type of social engagement, while in the second task cooperative communication was the most common. Only in the *Collaborative* condition did children use cooperative communication or informative gestures, and these engagements increased when collaboration was required. This may indicate that collaboration creates opportunities for information sharing and dialogue that are not present in social games. Children's learning about Maple improved with the *Collaboration* condition and perception of collaboration, and there was a significant interaction ($p = 0.03$) where children who perceived collaboration learned more when they were in the *Non-Collaborative* condition. Children who did not perceive collaboration learned more in the *Collaborative* condition. This result, however, hinges on the child in the *Collaborative* condition who did not perceive collaboration. Children's learning about making maple syrup was limited, with the highest score being two of six points. Also, several responses had to be removed from this analysis as children responded with outside knowledge about making maple syrup. While the average score increased with perceived collaboration, there were no significant effects for this.

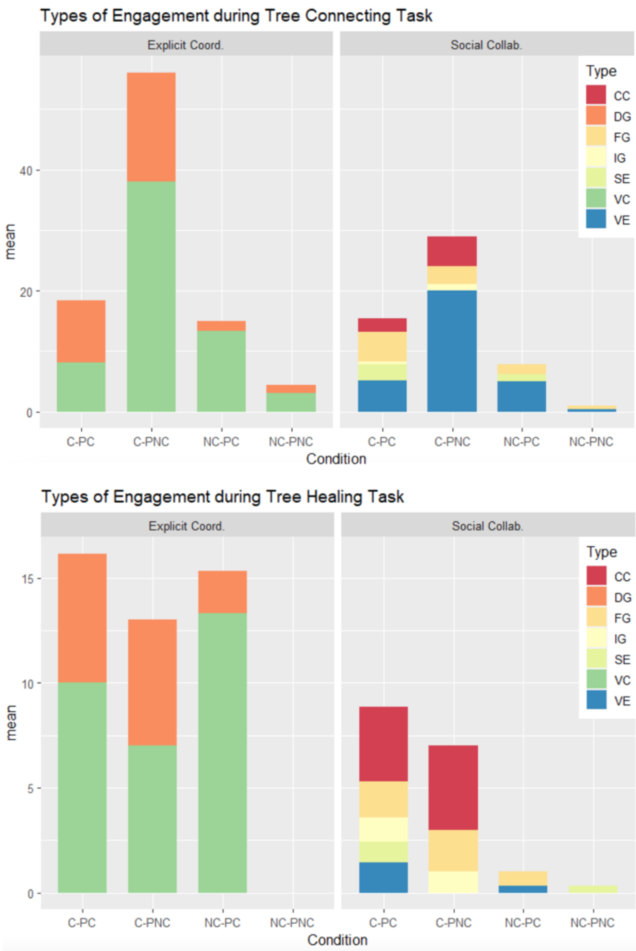

Fig. 5. Children's engagement by task, engagement, and condition.

IX. DISCUSSION

Our findings indicate several distinctions between the conditions and tasks that suggest further study on the effects of collaboration. Several results approached significance, notably with motivation increasing with the perception of collaboration. This suggests that when children believe they are collaborating – even if they are not truly doing so – they are more motivated to work on a task. Perceived collaboration also showed a trend to increase engagement, specifically in the non-collaborative condition. Thus, children demonstrate that they will try to engage even a non-humanoid robot if they believe they have shared goals. Lastly, we found that children behaved differently in different conditions, and with different beliefs about collaboration. For instance, when children did the collaborative task but did not think they were collaborating, they constantly directed the robot (explicit coordination). In contrast, social coordination increased in the collaborative condition overall, possibly because of the requirement to work with the robot to complete the tasks.

X. Conclusion and Future Work

We presented an overview of robots in education, provided a framework for collaoborative learning with robots, discussed opportunities for MAPLE in child-robot collaborations, and reported on a study that suggests that perceived collaboration with a robot can positively influence children's engagement and motivation, particularly in contexts where collaboration is encouraged but not explicitly required. Though we need a larger group for reliability, this work offers insights for advancing child-robot collaboration.

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