Design of an Assistive Robot for Infant Mobility Interventions

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***Abstract*— Childhood ambulatory disabilities detract from not only the physical development, but also the social engagement of young children. Commercial mobility aids can help improve the autonomy of children with disabilities, but affordability issues, policy challenges, and uncertainty about training standards limit early use of these devices. In this paper, we build on affordable research-grade mobility aids for young children and consider how to design and evaluate an assistive robot that can support the use of these devices. With young children's contingency learning abilities in mind, we designed an assistive mobile robot capable of supplying age-appropriate light, sound, and bubble rewards. We conducted a first evaluation of the robot's ability to support driving practice with N = 5 typically developing infants. The results indicate mixed success of the robot rewards; driving distances uniformly tended to fall over the course of the study, but children did tend to look at the robot. In a second exploratory study involving N = 6 children in free ambulatory play, we see clearer differences in gaze and behavior from the introduction of an assistive robot. Generally, this research can inform others interested in assistive robotic interventions for young children.**

I. Introduction

The U.S. Department of Health and Human Services estimates that 7% of children ages three to seventeen experience developmental disabilities [1]. Many of these conditions, including cerebral palsy, spina bifida, and Down syndrome (among others), affect children's physical abilities. However, high medical device costs, policy challenges, and a lack of commercial powered mobility solutions for infants limit early access to mobility aids [2]. At the same time, recent findings demonstrate the compounding value of early mobility; efforts in the last decade have demonstrated that toddlers with ambulatory disabilities engage in less variable physical activity, spatial exploration, peer interaction, and interaction with environmental objects compared to their typically developing peers [3]. Limitations in spatial exploration negatively affect the social and cognitive development of children with disabilities, so it is important to help these children gain access to suitable mobility support [4], [5]. Our work helps to address this need by contributing to *hardware* and *interaction design* for early mobility interventions like the example in Fig. 1 or body-weight-supported play.

Modified versions of readily available and affordable electric ride-on cars (typically marketed for toddlers) are one research-grade early mobility solution with evidence of developmental benefits [6], [7], [8], but the process of training infants to use these devices is not well understood [9]. Since research in child developmental psychology indicates that young children with disabilities are capable of learning contingent rewards when reinforcing stimuli are provided from the environment [10], [11], we propose an assistive robot with built-in reward capabilities for supporting early movement practice in powered mobility and other types of early mobility interventions (e.g., body-weight-supported play). Our *modular robotic system* is capable of supplying configurable *light, sound, and bubble-blowing rewards*. The main research goal throughout the paper is to understand how this robotic system influences young children's mobility behaviors in two different contexts (i.e., driving interventions and ambulatory free play) as a key step towards designing successful and novel future mobility interventions.

Fig. 1. Infant using a modified ride-on car to follow our assistive robot.

In this paper, after outlining key related work (Section II), we describe the design of our novel assistive robot (Section III). Section IV reports the protocols of our first study, which focused on child responses to the robot during robot-assisted powered mobility training. Results collected from five child system users indicate no improvement in driving performance based on robot presence, but children did tend to look at the robot when it was active (Section IV-B). Building off of this observed tendency, we designed a second exploratory playgroup study (Section V) which revealed more direct relationships between robot actions and robot-directed child behaviors (i.e., looking, touching, pushing/pulling, following, and approaching). Section VI details the design implications, strengths, and limitations of this work. Overall, this paper has *two main contributions*: 1) introduction of a novel and multipurpose robotic system for interactions with infants and 2) initial assessment of the robot's ability to assist in mobility interventions. To the best of our knowledge, this is the one of the first works on using robots to support infants' use of mobility aids.

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II. Related Work

The following key work on early mobility interventions and assistive robots guided and informed our research efforts.

Early Powered Mobility: Related research has focused on using modified commercial ride-on cars and wheeled robots as powered mobility devices. Past work on modified ride-on cars has evaluated car-based interventions in playgroups, increased mobility and socialization for a child with Down syndrome, and incorporated new features (e.g., rewards for standing) to facilitate motor skill development [12]. Ride-on cars are modified in two key ways to promote accessibility for young children with disabilities:

- A large, easy-to-press switch is installed on the steering wheel to allow for hand activation.
- Low-cost materials such as PVC pipe, Velcro, and pool noodles provide individualized seating support.

Additional work used a Pioneer robot base as an early powered mobility aid [13], which infants have controlled using joysticks [14], leg motion [15], and balance boards [16]. The powered mobility aid in our first study involved single-direction motion with an easy-to-use button input to investigate whether a robot can support simple driving skill training.

Other Early Mobility Interventions: Non-robotic rehabilitation alternatives to promote early motor development of children with mobility disabilities include manual wheelchairs [17], gait trainers [18], treadmills [19], and body-weight support harness systems [20]. In one promising intervention example, treadmill training resulted in infants with Down syndrome walking independently 100 days earlier than a control group who received standard of care [19]. Body-weight support harness systems are a more recent early mobility intervention with natural potential for (and early work in) robot-supported exploration, due to the potential for natural play during use [20]. Our second study builds on this previous work by using a controlled design to study the effects of a carefully designed assistive robot on child behaviors during an physical activity-focused playgroup.

Assistive Robots for Infant Development: Past work on assistive robot interactions with young children provided additional context for our efforts. Efforts with the NAO robot include a past study on using the NAO to demonstrate and reward leg-kicking motions [21]. The NAO, as well as the Dash robot, were also used in a smart learning environment for promoting physical and cognitive development through motor tasks [20]. Other work has used tabletop robots like Maki for teaching language to infants who are deaf [22]. The non-mobile Keepon robot successfully encouraged individual and collective social interactions during play with preschoolers [23]. Our efforts build on this past work by introducing an infant-sized mobile robot potentially capable of faster base motion and more compelling, age-appropriate play for infants than past assistive robot alternatives.

III. System Design

Our research efforts relied on updates to a modified ride-on car and design of an assistive robot. These steps were a close collaboration between the authors, who are split between robotics and kinesiology, to ensure the applicability of the end products in kinesiology-related domains. In early discussions, we identified these key system design criteria:

- Equipping a modified ride-on car with custom stop-and-go driving (for an initial proof-of-concept intervention) and improved data logging (for study data collection)
- Creating a mobile robot with developmentally appropriate motion, size, and reward capabilities
- Designing the robot for teleoperation by users (e.g., clinicians, parents) and future autonomous modes
- Designing safety measures (for both the child and the robot) into the system

The next subsections explain how we achieved these goals.

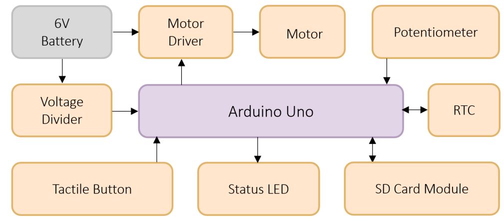

Fig. 2. Electronics overview for our modified ride-on car. Violet represents processors, orange represents other electronics, and gray represents power.

A. Modified Ride-on Car Updates

Our modified ride-on car base was a Fisher Price Power Wheels PAW Patrol Fire Truck capable of up to 2.5 mph speeds (Fig. 1). To facilitate the envisioned one-direction stop-and-go control, we locked the car's steering wheel in place and installed a 5-inch motor-activating tactile button over the wheel. The processor for car electronics was an Arduino Uno, and a motor driver module powered the 6V DC motors of the car, as shown in Fig. 2. To log button press and release times, we introduced a real time clock (RTC) module and recorded resulting data to an SD card. To maintain easy driving parameter adjustment by non-roboticists, we included a potentiometer in the system for adjusting car speed.

B. Assistive Robot Design

The design of the assistive robot can be divided into core robot design, usability design, and safety design.

Core Robot: The base of the robot is a Turtlebot 2, a robust, agile, commonly available, and commercial robot platform, which is controlled by a Raspberry Pi 3 B+ running ROS on Ubuntu 16.04. The Raspberry Pi communicates serially with the reward stack (further described below) and uses Bluetooth to communicate with a DualShock 4 controller. As shown in Fig. 3, we used long standoffs to raise the upper Turtlebot plate such that rewards are visible at infant eye level.

Based on the promise of contingent rewards in past assistive robotics work [21], we identified light-, sound-, and motion-based rewards as promising options for our assistive robot. Initial work in [24] uncovered human perception of different light signals for non-humanoid robots and informed

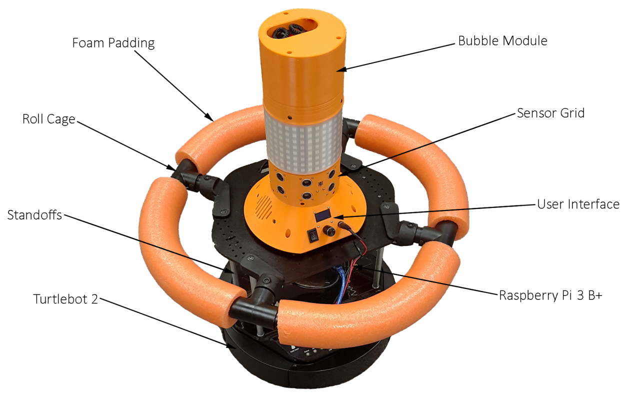

Fig. 3. The assistive robot base and reward stack.

our light reward pattern design. We drew inspiration from the infant toy market to select audio for sound rewards. Previous informal trials in the Social Mobility Lab demonstrated the appeal of bubbles; thus, we decided to implement a bubble-blowing attachment as our initial motion-based reward. Thus, our robot reward stack, as shown in Fig. 4, included light, sound, and bubble rewards. The reward stack includes an Arduino Mega Pro processor, comprises custom 3D-printed orange and clear PLA parts, and is powered by an external 12V power supply (i.e., power from the robot base).

Light rewards come from a flexible 8x32 RGB LED panel with individually-addressable lights (Fig. 4). The panel is placed behind a thin translucent PLA covering that diffuses light and protects the LEDs. Based on the expressive light signals proposed by [24], we developed six built-in animations (i.e., cross, still, pulse, fade, beacon, and wipe) with adjustable color and frequency. The user can also change pattern brightness and duration.

Sound rewards emerge from two 3-watt speakers on opposite sides of the reward stack (Fig. 4) for sufficient audibility. Before reaching the speakers, audio files stored on an SD card are played by a serial MP3 player and amplified by two 2.5-watt audio amplifiers. We curated the 200 built-in audio tracks based on four categories of sound commonly used in infant toys: animal noises, musical notes, household sounds, and baby noises. The user can customize sound loudness, number of audio track repetitions, and track clipping.

The bubble rewards come from a modular attachment that communicates with the reward stack via a D-Sub connector. This connection strategy supports the possibility to integrate other motion-based rewards in the future using a single common port. The reward stack automatically recognizes the presence and type of module using a simple voltage divider circuit-based strategy. Bubbles production over the module depends on two independent actuators: a geared motor that continuously dips wands in a bubble solution bath and a radial fan that blows into the emerging wands. The user can adjust reward duration and bubble density.

Usability: Interventions like the envisioned mobility aid training are typically run by kinesiologists, clinicians, and other non-robotics experts. Accordingly, the robot needed to be usable for individuals with little or no robotics experience. To facilitate seamless and varied use by non-roboticists, we included the OLED screen user interface (UI)-based, Dual-Shock controller-based, and infrared remote-based operation options shown in Fig. 5. An accompanying succinct one-page driving guide was created with sufficient detail to help non-roboticists seamlessly initialize and teleoperate the robot.

On the robot reward stack, an OLED screen-based UI with a rotary encoder/switch allows for fine-grained user customization of the light, sound, and bubble rewards. With the DualShock controller, users can drive the robot base, start/stop rewards, and adjust robot speed, as well as wirelessly update the OLED UI parameters. The infrared remote can communicate with an infrared sensor on the reward stack to start/stop rewards.

Although our first investigations involved human teleoperation of the robot, autonomous robot functionality is desirable for more scalable and precise future interventions. Accordingly, eight ultrasonic sensors were integrated around the reward stack for future proximity sensing.

Safety: A robot for interactions with young children also must be safe and robust; infants are vulnerable system users, and young children have commonly abused robots in past human-robot interaction studies in the wild [25]. The pre-existing modified ride-on cars offered good examples of hardware design features for safe and robust use by children (e.g., roll cages, affordable padding, hidden wiring, no pinch points). To protect both the assistive robot and the child in the case of a collision, a simple PVC-based roll cage was constructed around the upper plate of the Turtlebot and encased in foam padding. The use of teleoperation in the early studies described in this paper provided a further layer of safety; the teleoperator could choose to stop or change the robot motion at any time.

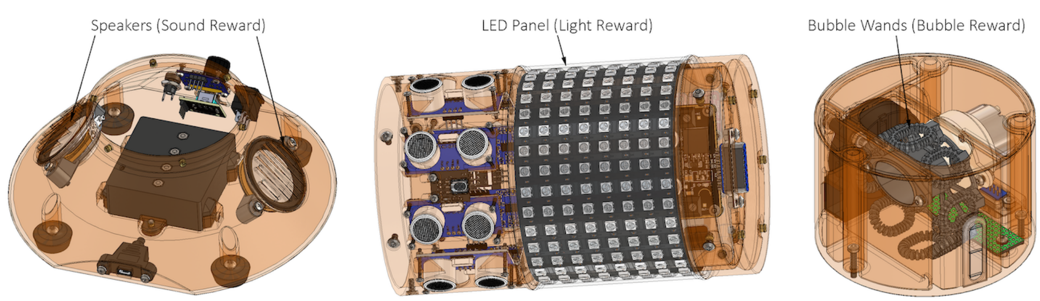

Fig. 4. Sections of the reward stack, from bottom to top. The transparency in this image reveals the inner hardware components (wiring not shown).

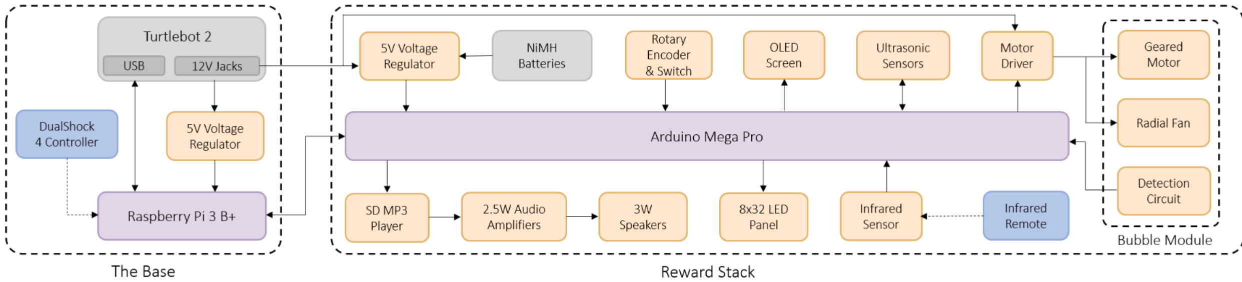

Fig. 5. Simplified overview of the electronics within the assistive robot, separated into the base (left) and reward stack (right). Violet represents processors, blue represents wireless components, orange represents other electronics, and gray represents power sources.

IV. First Study: Driving Intervention

Based on the driving training intervention of interest, our first exploratory study focused on assessing both differences in driving practice with and without a robot and differences in responses to robots with and without reward capabilities. The study used a single-case-style design to help control for the wide variation in behavior from infant to infant, as recommended as a best practice by past works such as [26]. The Oregon State University (OSU) Institutional Review Board approved this study under protocol #IRB-2019-0253.

A. Methods

The aim of our between-subjects first study was to investigate child responses to the assistive robot and effectiveness of robot-mediated driving training. All driving trials involved the use of a modified ride-on car, and treatment phases included two experimental conditions:

- *Robot motion* involved robot base motion only, with no light/sound/bubble rewards.
- *Robot motion + rewards* involved the same robot base motion as above, plus light/sound/bubble rewards as described further in the driving intervention details.

Half of the participants interacted with the robot motion condition, and half interacted with the motion + rewards. We hypothesized that the *motion + rewards condition would lead to longer driving distance attainment and more enjoyment than the motion condition*.

Behaviors, needs, and interests of young children vary greatly, so we used a single-case design with three phases:

- An initial *baseline* phase involving trials with no robot.
- A *treatment* phase involving trials with the assigned robot condition.
- A final *retention* phase involving trials with no robot.

Accordingly, we gained the ability to compare measurements not only across conditions, but also within participants (between the treatment and other phases). We hypothesized that the *treatment phase would elicit longer driving distances and more enjoyment than the baseline phase*.

Participants: Five male typically developing infants between twelve and 35 months of age ($M = 24.4$, $SD = 10.6$) and their parents participated in the study. Although the envisioned beneficiaries of the proposed intervention are children with disabilities, an initial test with typically developing children from the age range of interest allowed us to begin understanding the child-robot interaction before engaging with a more vulnerable population.

Driving Intervention: The first study took place in a gymnasium on OSU's campus. For participant comfort and safety, we assembled a 90 ft×10 ft (or approximately 27 m×3 m) grid of interlocking foam flooring squares (2 ft×2 ft each). One additional square centered at the start of the track served as the car starting point. As shown in Fig. 6, poly spot markers and cones appeared at 6-ft intervals along the course.

Before each driving trial, research assistants placed the modified ride-on car at the start of the track and the robot at the 6-ft marker, offset to the right of the car. The parent stood at the 30-ft cone and was allowed to supply minimal encouragement (excluding mention of features, parts, and behaviors of the robot or car). All research team members positioned themselves outside of the child's direct line of sight. Next, the infant was placed into the car without any instructions or demonstrations for how to activate the car; self-exploration is typical in early powered mobility training [9]. A researcher switched on the car power.

During all driving intervention trials, the goal was for the infants to activate the car and drive toward the parent. The parent moved to the 60-ft cone if the infant reached the 24-ft marker and the 90-ft cone if the infant reached the 54-ft marker. The driving trial ended if the infant reached the 90-ft cone, 90 seconds elapsed, or the infant began to climb out of the car, whichever occurred first.

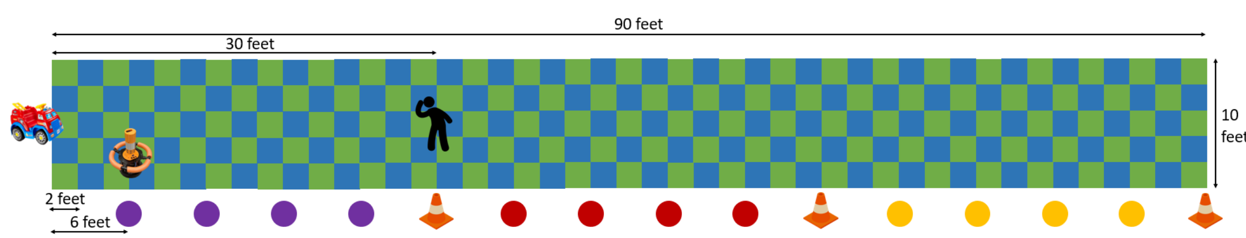

Fig. 6. Layout of the first study's driving track. The image shows the initial positions of the modified ride-on car, assistive robot, and parent.

We designed the study protocol and phases based on past work in [27]. In the *baseline and retention phases*, the robot remained motionless in its starting position. In the *treatment phase*, the assistive robot provided additional intermediate support via a cat-and-mouse-like interaction. For this first exploratory study, the robot was teleoperated by a study team member using a DualShock 4 controller. At the start of the trial, the robot made one small back-and-forth movement (for all conditions) and demonstrated the reward (for the motion + reward condition only). Once the infant drove within 2 ft of the robot, the robot advanced to the next marker (for the motion condition) or triggered the reward and moved to the next marker (for the motion + reward condition).

If the parent perceived infant distress, the child took a 5-minute rest period before the next trial. The modified ride-on car sometimes drifted; if the car traveled within 2 ft of the track's edge, a research assistant manually corrected the driving direction from behind the car. Qualitatively, infants did not seem to notice this course correction protocol.

Procedure: Participating infants and parents arrived at the study space for a two-hour *session* including three *phases* (baseline, treatment, and retention) made up of five driving intervention *trials* each. At the start of the session, the parent gave consent, completed an opening questionnaire, and selected appealing light and sound reward settings for their infant. The child next completed the baseline, treatment, and retention driving intervention phases, each followed by a parent questionnaire/semi-structured interview and 5-minute break. At the session's close, we conducted an interview with the parent and provided a $30 Amazon gift card.

Measurement: We used video recordings, car hardware, live annotations, questionnaires, and interviews to collect data. To capture infant head pose and facial expression data, GoPro cameras were mounted on the car and robot and a research assistant recorded session video using a handheld camcorder. Car button presses were recorded by an SD card. Annotators recorded the elapsed time for the child to reach each cone, as well as the total trial time and distance driven (estimated using the poly spots).

B. Results

For an initial high-level understanding of child and parent experiences, we focused on analyzing annotated driving data. A key challenge arising from the first study's design was that the infants grew more fatigued than expected over the course of the study, as is clear from the driving distance and velocity results in Table I. During the retention phase, two children were too agitated to complete and trials, and another child completed only two. Accordingly, there was no gain in performance when the robot was introduced. Some potential benefits of the robot motion + rewards condition (vs. motion alone) were apparent. Table II shows similarities in driving performance between the treatment and other conditions (i.e., no main effect from a repeated measures analysis of variance test with an $\alpha = 0.05$ significance level); however, on an infant-wise level, the decline in driving distance and speed was lower for the motion + rewards condition (mean reduction of 7.9 ft, 0.07 ft/s) than for the motion condition (mean reduction of 19.6 ft, 0.22 ft/s). (Note: 1 ft/s is roughly 0.3 m/s.)

TABLE I
MEAN AND STANDARD DEVIATION OVER ALL PARTICIPANTS' DRIVING PERFORMANCES DURING EACH STUDY PHASE.

	Baseline	Treatment	Retention
Driving Distance (ft)	52.4 ± 8.7	39.9 ± 7.9	33.0 ± 15.8
Average Speed (ft/s)	0.60 ± 0.10	0.46 ± 0.10	0.38 ± 0.21

TABLE II
MEAN AND STANDARD DEVIATION DRIVING PERFORMANCE ACROSS CONDITION DURING THE TREATMENT PHASE.

	Motion	Motion + Rewards
Driving Distance (ft)	41.0 ± 14.4	39.1 ± 4.3
Average Speed (ft/s)	0.46 ± 0.16	0.47 ± 0.10

From qualitative observations, we suspected that child gaze or focus may vary between driving with and without the robot. We used OpenFace [28] to conduct an exploratory gaze analysis. Due to challenges related to child face framing, only one child's video (from the motion condition) proved suitable for analysis. From usable frames, we calculated the percent of frames in which the child looked at the robot side of the play space (i.e., to their right). Usable frames were defined using the recommended OpenFace parameters (over 70% confidence level); 92% of frames were usable for baseline, 83% for treatment, and 62% for retention. For this child, we observed a tendency to increase in percent of time spent looking right during the treatment trials compared to the baseline trials, as shown in Table III. This child also tended to look this direction more during his two retention trials, although the reason for this is less clear. For example, it could mean that the child was looking earnestly for the robot or becoming fussy.

V. SECOND STUDY: AMBULATORY PLAY

From informal observations of children engaging in ambulatory play with the robot during the previous study and playgroups run by the OSU Social Mobility Lab, we wondered if the effects of the robotic system would be clearer in ambulatory or body-weight-supported play with the robot. This interaction is less related to the Social Mobility Lab's modified ride-on car mobility aids and more aligned with another of the lab's mobility aids: body-weight support system harnesses that counterbalance part of the user's weight and allow for free exploration and play within the system's footprint [20].

We accordingly conducted an exploratory second study in conjunction with a playgroup run by the Social Mobility

TABLE III
MEAN AND STANDARD DEVIATIONS OF PERCENT OF TIME GAZING AT THE ROBOT SIDE OF THE PLAY SPACE.

	Baseline	Treatment	Retention
Gaze at robot	4.5% ± 2.0%	13.3% ± 9.6%	17.2% ± 14.0%

Lab. The study again involved baseline and treatment phases to help account for the wide variations in each individual child's interests and abilities. The OSU Institutional Review Board approved this study under protocol #IRB-2019-0313.

A. Methods

The central aim of the second study was to investigate differences in playgroup member behaviors between sessions with an inactive robot and sessions with an active robot. All sessions had a robot present, and the behavior of the robot varied as follows:

- During four *baseline* phase sessions, the robot was powered off (i.e., not moving or supplying rewards).
- During three *treatment* phase sessions, the robot actively moved and used rewards.

Accordingly, we can compare overall group behaviors, as well as individual child tendencies, across the two types of session. We hypothesized that the *treatment phase would elicit more robot-directed behaviors than the baseline phase*.

Participants: Six children (one male, five female) and their parents participated in the study. Children were aged 1.6 to 6.7 years old (M = 3.6 and SD = 1.9). All participants in this study were Caucasian and typically developing. Attendance varied from session to session, as indicated in the results.

Although we recruited broadly for children with and without physical disabilities, none of the children who enrolled in this playgroup iteration used mobility aids. Thus, the present study serves as an exploratory look at the responses of children without disabilities to a robot in a setting and layout designed such that up to three body-weight-supported children could seamlessly be included in this type of playgroup in the future.

Procedure: Each of the hour-long sessions occurred during a playgroup that met weekly seven times with the same general cohort of children. For the Social Mobility Lab, the main goal of the sessions was free play for the children.

Four *sessions* comprised the baseline *phase* of the study, and the other three made up the treatment *phase*. (Further planned treatment and extinction sessions were cancelled due to the COVID-19 pandemic.) The same developmentally appropriate toys were present at every playgroup as visible in Fig. 7, and the behavior of the robot varied as noted above. During treatment sessions, the robot was teleoperated by a research assistant following a protocol that entailed moving around the play space in different patterns and attempting to engage with each child using each individual reward (i.e., lights, sounds, and bubbles) at least once per session. This design was meant to elicit children's natural responses to and play tendencies with the robot.

Measurement: We used videos to collect data. Two GoPro cameras mounted above the play space captured child behaviors throughout the session. Trained video annotators used momentary time sampling [29], in this case viewing video of the middle 30 minutes of the play session and fully annotating 2 of every 10 seconds. The codebook specific to the robot included codes for looking at the robot, touching the robot, pushing or pulling the robot, following the robot, and approaching the robot rewards. One coder annotated the full video and then re-annotated 10% of the total video time. Inconsistencies were discussed throughout the process, and the final percent agreement was 89.9%.

Fig. 7. Overhead view of a playgroup session. The view includes the developmentally appropriate toys included across all play sessions.

TABLE IV

MEAN AND STANDARD DEVIATION ROBOT-DIRECTED BEHAVIOR COUNTS OVER ALL PARTICIPANTS DURING EACH STUDY PHASE.

	Baseline	Treatment	Treatment (Final)
Look	0.08 ± 0.28	12.47 ± 13.51	4.17 ± 3.06
Touch	0.69 ± 1.03	6.65 ± 12.63	2.83 ± 2.64
Push/Pull	0.00 ± 0.00	1.18 ± 1.89	1.50 ± 2.51
Follow	0.00 ± 0.00	4.47 ± 6.76	0.33 ± 0.82
Approach	0.00 ± 0.00	2.53 ± 2.79	2.17 ± 2.32

B. Results

For an initial understanding of if our robot can gain child attention and encourage ambulatory child motion, we analyzed the averaged and individual robot-directed behaviors for each session. From the interaction premise updates between the first and second studies, differences due to the robot appear much more clearly.

Based on the example of seminal work in contingent reward learning with and without robots [21], [30], we defined a change in child behavior due to the robot treatment as an increase of 1.5 times or more from baseline to treatment. Table IV shows that the robot-directed behaviors uniformly change in a positive direction between the baseline and treatment phases. Looking at the group holistically is reasonable since group interactions differ from one-on-one interactions [31], but investigating individual child responses can also inform our future work in intervention settings. Fig. 8 reveals that individual child behaviors trend in the same way, although individual tendencies vary somewhat. 100% of children looked at the robot more during treatment sessions than baseline sessions. The incidence of child-wise increases in touching, following, and approaching the robot rewards were all 83%. 50% of children increased their levels of pushing or pulling the robot during the treatment phase.

The effect of novelty is clear in the data, so the incidence of child behavior changes when looking just at the final session merits exploration. Looking just at these values,

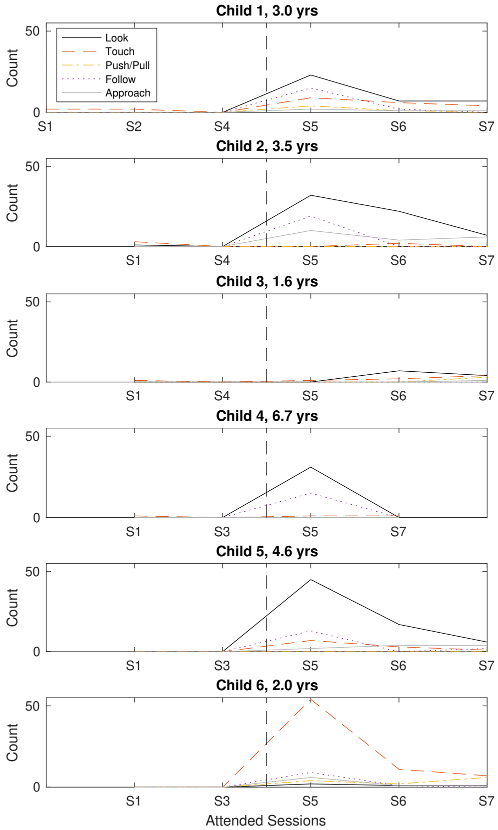

Fig. 8. Changes in robot-directed behaviors of individual children between baseline and treatment sessions. The x-axis tick labels denote which sessions each child attended. The vertical dashed line shows the transition from baseline to treatment.

Fig. 9. Observed categories of interaction with the robot. *Top Left:* pretend play. *Bottom Left:* reward-based attention. *Top Right:* using the robot as a cruising toy. *Bottom Right:* robot use to augment toys.

child-wise levels of change drop, but the differences are still there even after nearly a month of playing with the robot. The final treatment phase values (final column of Table IV) maintain that the robot-directed behavior frequencies are all still higher during treatment, even when just considering the final session. Rates of increase in child-wise touching and approaching rewards stayed the same at 83%. Increases in all other behaviors fell slightly; the updated increases in looking at, pushing or pulling, and following the robot fell to 83%, 33%, and 17% respectively.

Lastly, we noted emergent play paradigms between children and the robot. To the best of our knowledge, this is one of the first studies of a mobile robot in unstructured group play settings in the United States. Accordingly, the observed play behaviors can help to inform future interaction paradigms in the proposed intervention space. Example images in Fig. 9 show the four main observed types of behavior: pretend play (e.g., holding a phone up to the robot's "ear" and saying "Hello"), pursuing or studying robot light and bubble rewards, physically interacting with the robot (e.g., touching the robot, using the robot as a walker or foot rest), and using the robot to augment toys (e.g., by swirling play balls around the robot's roll cage).

VI. Discussion

The first study indicates mixed success of robot-mediated driving interventions. Neither of our hypotheses were supported; driving performance tended to fall over the course of the study as infants appeared to become more tired. At the same time, the motion + rewards robot intervention condition tended to lessen the decline in performance. Children tended to look at the robot when it was present, indicating that the robot behaviors are eye-catching. Developmental stage of participants may play a key role. Most participants were already walking and tended to want to climb out of the car and explore on foot. Two participants (one per condition) were not yet walking, and the child in the motion + rewards condition had a steady increase in driving distance and speed across phases. Thus, design improvements for this type of robot-mediated driving support include shorter practice sessions (or sessions with longer breaks) and system users on the younger end of our previously studied age range.

The second study reveals clearer beneficial trends; in this case, children both look at the robot more and engage with it more when it is active, compared to during baseline sessions. This pattern holds true even when we consider only the final treatment phase, when the playgroup participants have been interacting with the robot for nearly a month. These observations provide a helpful foundation for future body-weight-supported motor interventions. At the same time, the apparent novelty effect means that future robot applications will need varied behaviors and rewards, for example, new light patterns, updated sound libraries, and moving elements like streamers or pinwheels. The ideal age range for the future envisioned body-weight-supported play may be 2-3 years old; children in this age range tended to approach and touch the robot, sometimes even using it as a walker of sorts. These tendencies support the robot's ability to attract child attention and encourage them to move around the play space.

One key *contribution* of this work is the design of a novel assistive robot from active collaboration between roboticists and kinesiology experts. The presented studies are an important step toward wider use of robots to support mobility interventions. The *limitations* of this work include having a small participant group without disabilities, without mobility aid use, and with unbalanced gender. We also conducted our investigation in a lab setting, rather than in a more natural setting like a clinic or home. Building from the present results, our *next steps* will include updating intervention and interaction designs according to our discussed insights and performing larger empirical studies to better understand the effects of robot-mediated mobility interventions.

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