Using a Socially Assistive Humanoid Robot to Encourage Infant Leg Motion Training

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Abstract— **Early interventions have the potential to positively influence infant movement patterns and support optimal neurodevelopmental outcomes. This work developed and validated a non-contact socially assistive infant-robot interaction system that aimed to use contingent reward learning and imitation to deliver effective early interventions that complement human-delivered therapy.**

The described study explored if infants demonstrate contingent learning and imitation behavior in response to movements by a similarly-sized NAO humanoid robot. Twelve 6- to 8-month-old infants participated in a within-subjects study that compared different robot contingent reward policies for encouraging leg movement. Nine of the twelve participants learned the contingency. Of these learners, two responded less to the movement and lights reward than other rewards. Nine of the twelve infants imitated the NAO robot during at least one reward condition phase. These imitators displayed different learning rates and sometimes changed their behavior to imitate less during later reward conditions. Infants were generally alert and non-fussy when interacting with the robot. Parents of participants perceived the robot reward involving both movement and sound to be most engaging for their children.

To the best of our knowledge, this work is the first foray into using socially assistive robots with infants. As this new research area develops, our results aim to inform continued work into targeted robot-assisted infant motion interventions.

I. Introduction

Socially assistive robotics (SAR) has demonstrated potential to benefit a broad range of populations, from children with developmental delays [1] to older adults facing health challenges [2]. The research presented in this paper introduces SAR into a new domain: teaching and reinforcing infant motion. As a first foray into socially assistive infant-robot interaction, this work aims to gain novel insights into such interactions and inform targeted robot interventions for infants.

Motor exploration and the practice of motions are essential facets of infant development. Learning to perform actions from grasping a favorite toy to kicking with knee extension have a substantial impact on infant cognitive and motor development. Some infants, especially those at risk for developmental delays, move an insufficient amount or practice non-optimal movement patterns. This tendency can lead to inadequate development of age-appropriate strength, proprioception, and coordination. A recent estimate determined that approximately 9% of infants born in the United States are at-risk and could benefit from early targeted interventions [3].

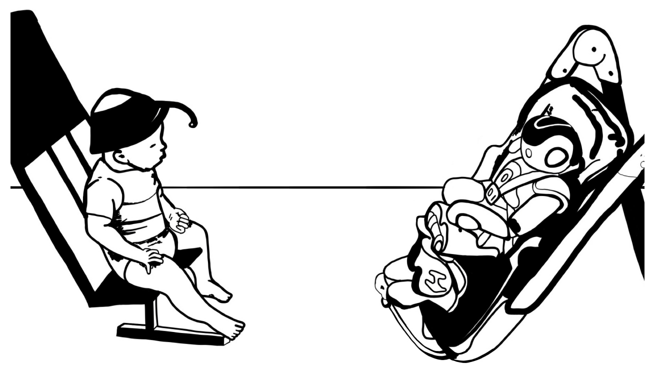

Fig. 1. The infant-robot intervention scenario. An infant-sized socially assistive robot sits facing the infant and interacts with the infant using non-contact modalities such as motion, light, and sound.

Although early, frequent, and targeted interventions for at-risk infants have the potential to improve these infants' neurodevelopmental function, the state of the art in motor interventions for at-risk infants is infrequent low-intensity movement therapy [4]. Accordingly, this work introduces SAR in the form of a humanoid infant-sized robot intended to teach, promote, and reinforce desirable types of infant motion. The robot assists infants through non-contact interventions like the one pictured in Fig. 1. Such SAR-supported therapy is more scalable than the state of the art and could promote infant motor practice more regularly in homes and other accessible everyday environments.

Past infant behavior research highlights contingency learning and imitation as two infant behaviors that could be leveraged to support robot-based motor interventions. Specifically, infants as young as three months old can become motivated to perform particular actions to gain a reward like the motion and sounds of an overhead mobile [5]. Infants also demonstrate the capacity to imitate, for example by

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producing motor actions modeled by a parent [6]. As a first step toward enabling SAR use for scalable infant motor interventions, we aimed to understand whether behaviors like contingency learning and imitation also apply to infant-robot interactions. If infants imitate robot motion or robot rewards motivate infants to move in particular ways, then SAR holds promise for targeted infant-robot interventions. Before working with more vulnerable at-risk infants, we conducted a study to learn how infant contingency learning and imitation behaviors observed in child-toy and child-adult interactions manifest in interactions between a typically developing infant and a robot. In this article, we focus on answering the following questions:

1) *Do robot actions serve as a contingent reward* for motivating infant leg motion?
2) *Do infants imitate robot motions*, as defined by our proposed exploratory definition?
3) *How do parents perceive child-robot interaction*?

Answering these questions forms the necessary foundation toward developing socially assistive infant-robot interactions that improve neurodevelopmental outcomes.

This article summarizes related work (Section II), describes our methods for conducting a study of typically-developing infant interactions with a small humanoid robot (Section III), presents the results of the study (Section IV), and discusses our findings (Section V).

II. Related Work

To evaluate the potential of SAR for infant motor interventions, we first consulted related literature on infant responses to contingent rewards and infant imitation tendencies. We reviewed work on infant interaction with adults and toys, as well as past studies of infant motor delays and infant-robot interaction. In the following sections, we outline the background literature that motivated the design of our study, explained the need for interventions in this space, and demonstrated the potential of SAR.

A. Socially Assistive Robotics Foundations

SAR research aims to use non-physical human-robot interactions to aid people with various needs [7]. These interactions often focus on supporting behavior change. For example, researchers have successfully used SAR to motivate adults to participate in post-stroke physical therapy interventions [2] and coach children with autism spectrum disorder through social interaction practice [1]. SAR can provide cost-effective methods for maximizing the user's motivation both during and after structured training, therapy, or rehabilitation sessions. Additionally, SAR allows for continued interventions outside the limited scheduled structured sessions.

Past work has repeatedly shown that physically embodied robots are more effective at persuading and motivating users than on-screen agents [8]. Other past efforts demonstrated that children from 6 to 14 months old look at a humanoid robot for longer than an android or an unknown person [9]. The extensive literature on mirror neurons (e.g., [10]) further suggests that interactions with an infant-sized humanoid robot may naturally lead infants to imitate and practice key motor skills like kicking with knee extension. These precedents in SAR and neuroscience led us to select the Aldebaran NAO robot as a SAR agent for our proposed infant-robot intervention system. We previously demonstrated the potential of such a robot; in our past data collection, infants became more alert and directed their visual gaze to a NAO robot while it moved [11].

B. Infant Motor Delays

Infants who display early motor delays often have the initial signs of later developmental impairments. Motor, cognitive, and social development of infants are strongly interrelated, so an early deficit in one developmental domain can substantially affect all three domains. Accordingly, it is important to provide early interventions for infants to ensure the development of all three domains [5].

The current standard of care for early intervention with infants is to provide infrequent, low-intensity movement therapies [4]. This approach is insufficient; both basic science and clinical evidence support that early, intense, and targeted therapy interventions are more effective than the standard care approach for promoting improved neurodevelopmental structure and function [12]. A scalable system like the one proposed in this work could be used in both structured therapy and home environments to offer personalized care that adapts to user abilities and needs.

C. Infant Motor Learning and Adaptation

Infants engage in exploratory movements that allow them to learn the connection between their body and the physical world [13]. For instance, when 9-month-old infants are placed in a jumper toy, they adjust the timing and force of their leg movements to optimize bouncing [14]. Additionally, spontaneous infant movements modulate into task-specific actions such as reaching, crawling, and walking [13]. The dynamic process of how motor exploration and discovery leads to task-specific actions is a topic of active research. Multiple studies have observed this exploration-exploitation learning process, but such work generally provides limited quantitative information about the infant movement. Our work offers key insights in this area through the use of data acquired with wearable inertial sensors that track infant limb movement during motor exploration.

An established technique for observing the emergence of task-specific learning from spontaneous movement is to provide an infant with contingent feedback when the infant produces a specific desired movement. Historically, such infant contingency studies used a mobile paradigm where the infant's arm or leg is attached to an overhead mobile with string [15]. The more the infant moves the connected limb, the more sound and motion is generated by the overhead mobile. Early work used this paradigm to study learning and memory in early infancy. More recent studies have demonstrated that infants can increase their leg kicking rate [5] and perform selective hip-knee intralimb coordination (e.g., hip flexion with knee extension) [16] when such behavior is reinforced by mobile motion.

Although these studies demonstrate that infants as young as 3 months old can consistently learn different types of reinforced motion patterns, it remains unclear how kinematic data such as the acceleration of a movement should be used to activate rewards. One goal of this work is to create an infant-robot system for contingent feedback wherein the inertial information gathered from the infant can activate various robotic rewards. An additional goal of our work is to observe which rewards stimulate the most infant motion.

Infant imitation is an active area of interest in infant learning research. For example, researchers assess infants' ability to reproduce motor actions performed by their parents [6]. Related literature suggests that infants use imitation as one mechanism for the acquisition of new behaviors, skills, and actions. For example, in one study, 6-month-old infants who observed a researcher removing and replacing a mitten on a puppet were more likely to perform that action than those who did not observe this behavior [17]. It is not yet known if infants perceive human actions differently from humanoid robot actions resembling human behavior, but our work aims to help the research community understand if infants tend to replicate humanoid robot motions.

III. Methods

We conducted a within-subjects infant-robot interaction study to learn 1) whether robot behavior can be used as a contingent reward for motivating infant leg motion; 2) whether infants imitate robot behavior; and 3) how parent perceptions of the child-robot interaction compare to measures of infant motion and behavior. The experimental procedures described throughout this section were approved by the University of Southern California Institutional Review Board under protocol #HS-14-00911.

A. Participants

We recruited twelve typically developing 6- to 8-month-old infants from the greater Los Angeles area to participate in our study. We selected the 6-8 month age range because infants can learn contingencies before 6 months of age (e.g., [16]), and 6 months of age is a common time for related work to begin assessing the type of movement behavior we are studying (e.g., [6]). Table I displays the age, size, and development information for each infant.

B. Study Setup

Based on the literature discussed in Section II and our pilot study results [11], we chose the Aldebaran NAO humanoid robot for our infant-robot interventions. In the experimental setup, the NAO robot and infant sat facing one another in a small room with white walls and minimal visual distractions, as shown in Fig. 2. The chair where the infant sat allowed for full leg mobility. Infants wore APDM Opal inertial sensors on both arms and legs so we could measure the tri-axial acceleration and angular velocity of each limb.

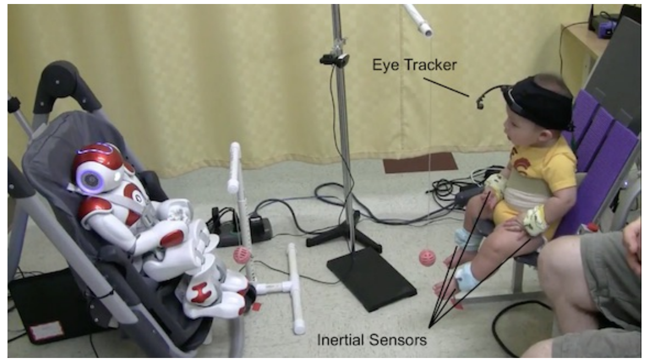


Fig. 2. The experimental setup. The infant interacts with a NAO robot while the labeled sensors (an eye-tracker and inertial sensors) and additional sensors (RGB cameras and a Kinect One RGB-D sensor, not shown in the field of view of this image) capture information about the infant-robot interaction.

Infant participants also wore a head-mounted eye tracker, and three RGB cameras and a Microsoft Kinect One RGB-D camera captured front, side, and face views of the infant. The setup included two suspended toy balls, one that the robot could kick with the left leg and the other the infant could kick with the right leg. This object setup was informed by past work showing that instrumental behavior (e.g., kicking a ball) motivates infants more than spontaneous behavior (e.g., kicking for the sake of kicking) [18].

C. Manipulated Variable

In addition to learning how to encourage infant motion, a key goal of this study was to determine what types of robot rewards would be most effective for encouraging infant motion. Accordingly, the manipulated variable in this study was the *type of contingent reward*. In the within-subjects study design, each infant experienced three types of contingent rewards in three separate phases. To avoid ordering effects, the condition order was counterbalanced and randomly assigned to participants. The three reward types for achieving leg movements above the acceleration threshold were:

1) **Movement Alone:** The seated robot extends its left leg and taps the suspended ball.
2) **Movement and Lights:** The seated robot extends its left leg and taps the suspended ball while all the LEDs on the robot rapidly and continuously change color using the NAOqi library's rasta() function.
3) **Movement and Sound:** The seated robot extends its left leg and taps the suspended ball while performing pre-recorded infant babbling noises.

D. Procedure

Each infant was brought to the lab for a single hour-long session. Before scheduling the visit and again when the parent and infant first entered the experiment space, the parent or legal guardian (heretofore referred to as "parent") received a written overview and verbal explanation of the procedures. The parent signed an informed consent form prior to the infant's participation. We affixed one Opal

TABLE I
DEMOGRAPHIC INFORMATION FOR THE STUDY PARTICIPANTS.

Infant	Gender	Age (days)	AIMS Score	AIMS Percentile	Weight (kg)	Head Circumference (cm)	Body Length (cm)
TD2	F	183	19	10	6.60	43.0	66.0
TD3	M	258	35	30	7.28	45.5	69.0
TD4	M	264	37	20	8.00	46.0	69.0
TD5	F	211	30	50	10.10	44.0	72.0
TD6	F	226	38	80	7.05	43.5	65.0
TD7	M	195	18	5	6.66	43.5	67.5
TD8	M	191	30	65	7.57	44.0	65.0
TD9	M	194	28	50	8.50	43.5	68.0
TD10	F	183	22	25	6.23	41.5	62.0
TD11	F	182	27	58	8.08	42.0	65.0
TD12	F	206	29	50	7.80	43.0	70.0
TD13	F	188	25	30	7.20	42.0	68.0

inertial movement sensor to each infant limb using custom-made leg warmers with pockets. We also attached a head-mounted eye tracker to the infant.

The infant was then seated in a chair across from and facing the NAO robot, as shown in Fig. 2. The parent sat adjacent to the infant. We measured the infant's baseline movement level while the infant sat in the pictured setup facing a motionless robot for two minutes. During this phase, the parent occasionally engaged with the infant in an effort to maintain interest and prevent fussiness; otherwise, the parent was asked not to interact with the infant. The infant then entered the eight-minute contingent reward portion of the experiment during which the reward conditions ran for $2\frac{2}{3}$ minutes each. To help maintain infant attention and satisfaction, there was no break between sequential reward phases. Next, a so-called "extinction" phase of two minutes occurred. In the contingent learning literature, the extinction phase is the interval when the reward is removed. In our study, the robot ceased to move and react during the extinction phase.

At the start of the first contingency condition, the robot demonstrated three sequential knee extension ball kicks with the left leg. After that, the robot only moved when the infant moved above the set acceleration threshold. A video with clips of different procedure phases is available in the supplemental material included with this article.

After the infant-robot interaction, the parent completed a survey on their perceptions of the infant's experiences. A research team member administered the Alberta Infant Motor Scale (AIMS) assessment [19] to quantify the infant's motor development status. Infant weight, length, and head circumference were also measured. Each participating family received $40 of compensation for completing the study.

E. System Architecture and Behavior Control

We designed a system architecture that allowed for real-time use of sensor readings to trigger robot responses, as shown in Fig. 3. Throughout the session, the Opal sensors provided data to the robot. Using synchronized streaming, the raw inertial sensor data was sent to an off-robot computer. There, the system calculated the instantaneous acceleration of each infant limb at 128 Hz using the quaternion filter supplied by the Opal sensor's software development kit. The

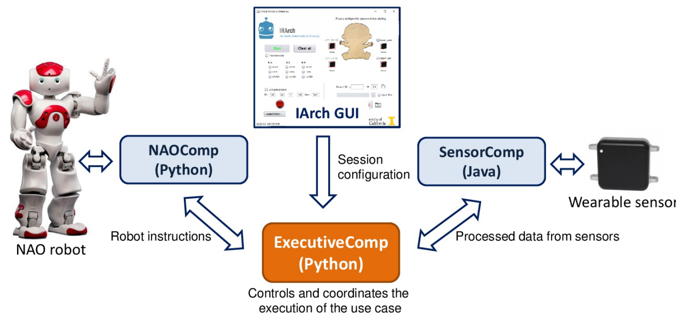


Fig. 3. The SAR intervention system architecture designed to integrate the inertial sensor data into the robot's contingent behavior response.

acceleration information was provided to the robot to drive its response behavior.

During the portions of the study involving contingent rewards, the robot reward behavior was activated when the infant's right leg moved above a resultant acceleration threshold. This acceleration threshold was determined based on our previous work [20]; we found a threshold of 3.0 m/s^2 to be appropriate for detecting leg movements in the root sum of squares signal from the three filtered accelerometer axes. During the robot's reward behaviors, the infant movement perception system paused and did not monitor for new acceleration over the threshold until the robot finished executing its reward condition behavior. Because of the way data were collected, any infant movements above the acceleration threshold that occurred during the robot reward kicks (each approximately 1.2 seconds in duration) were not considered in our later contingent learning analysis.

F. Hypotheses

This study tested the following three main hypotheses:

H1: Learning the Contingency: The majority of the infants will learn the contingency, i.e., they will move their right leg above the acceleration threshold at a rate of 1.5 times or greater in one or more of the contingency phases than during the initial baseline. This hypothesis aligns with the findings from past work like [5], where infants learned to move in a particular way to gain contingent rewards.

H2: Imitation: Infants will tend to imitate the NAO robot by kicking the ball in front of them with a knee extension movement. Past work in the mirror neuron literature [10] suggests that an infant may naturally imitate a similarly-sized humanoid robot. This is part of the motivation for using a robot in this work and for selecting the NAO robot in particular. At the same time, imitation is not as well understood as contingent learning, and this hypothesis is exploratory.

H3: Parent Surveys: The parents' perception of infant behavioral state and contingency learning will provide additional insights beyond the quantitative and qualitative data collected from the infants. Since the parents are present in the lab and able to observe the infant's behavior, parent insights may augment our understanding of their child's experience.

G. Data Collection

During the study, we tracked the following aspects of the infant's state: physical responses (i.e., motion measured by inertial sensors), visual responses (i.e., eye gaze), and behavioral state responses (i.e., infant alertness level). We collected physical response data from the arm- and leg-worn Opal inertial sensors and gaze direction data from the head-worn eye tracker. Three RGB cameras and a Microsoft Kinect One RGB-D camera captured front, side, and face views of the infant for post hoc assessment of infant behavior.

A reliability-trained video coder annotated the behavioral state of the infant throughout the study using an established five-point arousal scale with the following anchor points: sleeping, drowsy, crying, fussy, and alert [16]. A trained video coder also annotated each infant leg movement as one of four categories (knee flexions, knee extensions that did not result in contact with the ball, knee extensions that did result in contact with the ball, or other leg motions) using camera footage from the study.

In a post-study survey (administered on paper), we asked the parent 1) to rate the emotional state of the infant during the study on the Self-Assessment Manikin (SAM) pictorial scales; 2) which conditions kept the infant the most engaged; and 3) if the parent perceived the infant to be imitating the robot. Each response was recorded on a 5-point Likert scale.

IV. Results

As stated in Section I, our goal in this work was to study if infants can learn from robot-provided contingent rewards, if infants tend to imitate a small humanoid robot, and how parents perceive the infant-robot interaction. All infants in the study successfully completed the procedure; our participant numbering method begins at TD2 because an initial participant, TD1, was our pilot system user. This section outlines infant motion tendencies throughout the study, imitation results, behavioral state results, and parent perceptions of the study interaction.

A. Infant Motion Results

Conceptually, contingent learning occurs when infants learn the connection between their behaviors and some emergent result in the world around them. Based on the example of seminal past work in contingent reward learning [16], we *defined learning the contingency* as the infant moving the right leg above the acceleration threshold at a rate of 1.5 times or greater in one or more of the contingency phases than during the initial baseline. By analyzing the inertial data gathered during different study phases for number of leg movements over the acceleration threshold, we can assess whether this increase occurred. We used the infant's baseline (initial two minutes of movement recorded before the robot began moving) as a basis for comparison against subsequent infant motion because this initial baseline represented the original infant state without any influence from the robot.

As illustrated in Table II, nine of the twelve participating infants learned the contingency. Of those learners, two responded less to the movement and lights reward than other rewards; for TD9, this was the first reward condition, and for TD11, it was the second. The rest of the infants more frequently moved above the acceleration threshold in response to all rewards. Since infants usually demonstrated contingent reward learning during all or none of the reward phases, the temporal order of conditions does not seem to be an important factor in our analysis.

We also evaluated whether infant movement differed significantly across the reward conditions using a one-way repeated measures analysis of variance test (rANOVA) with an α = 0.05 significance level. Post hoc Tukey multiple comparisons tests revealed which pairs of conditions had statistically significant differences. As illustrated in Fig. 4, significant differences in the frequency of infant leg motion above the acceleration threshold appeared over experiment phase ($F(3,33) = 8.00$, $p < 0.001$, $\eta = 0.192$). The infant leg movement frequency was higher for all reward conditions than for the baseline reading. No significant differences in infant motion occurred between the reward phases.

B. Imitation Results

Imitation occurs when infants replicate observed behavior of humans (or in this work's case, humanoid robots). Operationally, imitation is often defined as an increase in the performance of some behavior after observing it. Thus, like in the contingency learning results, we *defined infant imitation of the NAO robot* as the infant performing the knee extension ball-kicking motion at a rate of 1.5 times or greater in one or more of the reward phases than during the initial baseline. Our trained video coder's counts of ball-kicking motions throughout the study procedure yielded the information needed to perform this analysis. We used the infant's baseline as a basis for comparison against later ball kicking frequencies.

As shown in Table III, nine of the twelve participating infants exhibited imitation behaviors during as least one reward phase. One infant (TD2) imitated the robot during all reward phases. For imitators who did not consistently

TABLE II

FREQUENCY OF INFANT MOTION ABOVE THE ACCELERATION THRESHOLD DURING THE STUDY PHASES. THE THIRD COLUMN INDICATES THE LEARNING THRESHOLD: THE LEG MOVEMENT RATE REQUIRED TO CONCLUDE THAT THE INFANT HAS LEARNED THE REWARD. SHADED HEADINGS MATCH LATER PLOT COLOR CODING. GRAY BOXES INDICATE PHASES DURING WHICH CONTINGENT REWARD LEARNING OCCURRED.

Infant	Baseline (moves/min)	Learner Thresh (moves/min)	Movement Reward Activity (moves/min)	Movement + Lights Reward Activity (moves/min)	Movement + Sound Reward Activity (moves/min)	Extinction (moves/min)
TD2	4.00	6.00	11.62	15.75	18.37	12.00
TD3	10.00	15.00	10.87	7.87	8.25	6.00
TD4	5.00	7.50	25.12	16.50	12.00	4.50
TD5	6.00	9.00	11.62	14.62	15.00	8.00
TD6	17.50	26.25	25.87	16.12	10.50	17.00
TD7	14.50	21.75	14.62	15.00	18.37	9.50
TD8	5.00	7.50	11.25	26.25	16.12	16.50
TD9	4.50	6.75	13.87	5.25	13.50	10.50
TD10	5.00	7.50	18.37	12.75	17.25	9.50
TD11	10.50	15.75	27.00	14.62	25.50	14.50
TD12	20.00	30.00	34.12	33.75	33.00	19.00
TD13	2.00	3.00	3.37	7.12	14.25	10.00

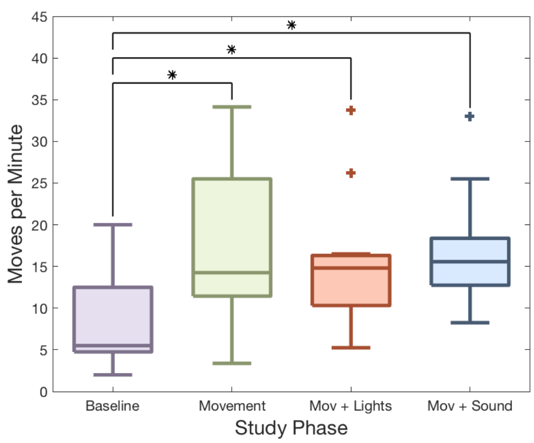


Fig. 4. Frequency of infant motion above the acceleration threshold across study phases. The center box lines represent the median, and the box edges are the 25th and 75th percentiles. The whiskers show the range up to 1.5 times the interquartile range, and outliers are marked with a "+". Brackets indicate significant differences as determined by the post hoc multiple comparisons test.

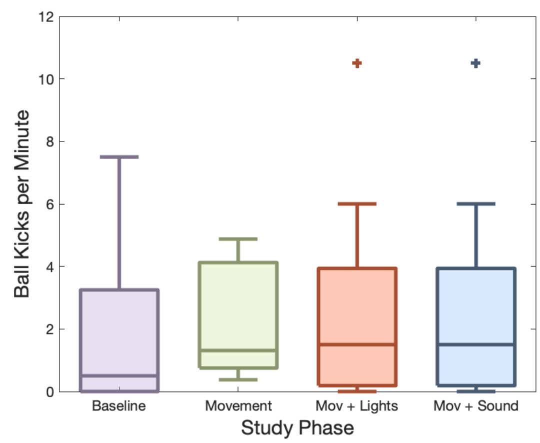


Fig. 5. Frequency of infant ball kicks across study phases. The center box lines represent the median, and the box edges are the 25th and 75th percentiles. The whiskers show the range up to 1.5 times the interquartile range, and outliers are marked with a "+".

imitate the robot across all reward phases, the temporal aspects of their imitation may prove helpful for designing follow-up studies. Three infant (TD4, TD5, and TD9) failed to imitate the robot during the first reward phase that they experienced but imitated the robot during the remainder of the reward phases. Two infants (TD6 and TD8) imitated the robot during only the second reward phase that they experienced. TD7 imitated the robot until their final reward phase, TD12 imitated the robot only during their first reward phase, and TD13 only imitated the robot during the final reward condition that they experienced.

Thus, we found that it is most common for infants to experience one or two reward phases before they initiate (or demonstrate) imitation of the robot kicking the ball. Some infants stopped imitating the robot during later phases. These tendencies may indicate that infants take longer to learn to imitate the robot than to learn the contingent rewards discussed previously. Our video data suggested that some infants kicked the ball deliberately. The perceived effort expressed by some participants may have led to fatigue or boredom at sufficient levels to halt imitation of the robot during later reward phases. Overall, these initial results demonstrate that some young infants may imitate a humanoid robot, but follow-up research is needed. Some infants did not kick the ball at all during baseline, and so they only needed to perform a few ball kicks during the reward conditions to be classified as imitators. Future work will be needed to investigate what aspects of action the infants strive to imitate and explore the tendencies of infants to imitate other types of motions or behaviors.

C. Behavioral State Results

Infant behavioral state coding revealed that infants were almost always alert. No infants were drowsy or sleeping during the study. During the total duration of the study, infants were alert 94.2% of the time, fussy 4.3% of the time, and crying 1.5% of the time on average. Figure 6 displays a more in-depth breakdown of each infant's behaviors across

TABLE III

FREQUENCY OF INFANT BALL-KICKING MOTION DURING THE STUDY PHASES. THE THIRD COLUMN INDICATES THE IMITATION THRESHOLD: THE BALL-KICKING RATE REQUIRED TO CONCLUDE THAT THE INFANT IMITATED THE BEHAVIOR. SHADED HEADINGS MATCH PLOT COLOR CODING. GRAY BOXES INDICATE PHASES DURING WHICH IMITATION OCCURRED.

Infant	Baseline (ball kicks/min)	Imitation Thresh (ball kicks/min)	Movement Reward Activity (ball kicks/min)	Movement + Lights Reward Activity (ball kicks/min)	Movement + Sound Reward Activity (ball kicks/min)	Extinction (ball kicks/min)
TD2	0.00	0.00	4.12	6.00	2.625	1.00
TD3	0.50	0.75	0.375	0.00	0.375	0.00
TD4	0.00	0.00	1.12	0.00	2.25	0.00
TD5	0.00	0.00	1.12	2.25	0.00	0.00
TD6	0.50	0.75	1.50	0.00	0.00	2.50
TD7	6.00	9.00	4.87	10.50	11.25	9.00
TD8	2.50	3.75	0.75	3.37	3.75	2.50
TD9	0.00	0.00	0.75	0.375	0.00	0.00
TD10	4.00	6.00	4.87	4.50	4.12	2.50
TD11	7.50	11.25	4.12	0.75	0.37	1.00
TD12	0.50	0.75	0.37	0.37	0.75	2.00
TD13	2.00	3.00	2.25	3.37	1.50	3.50

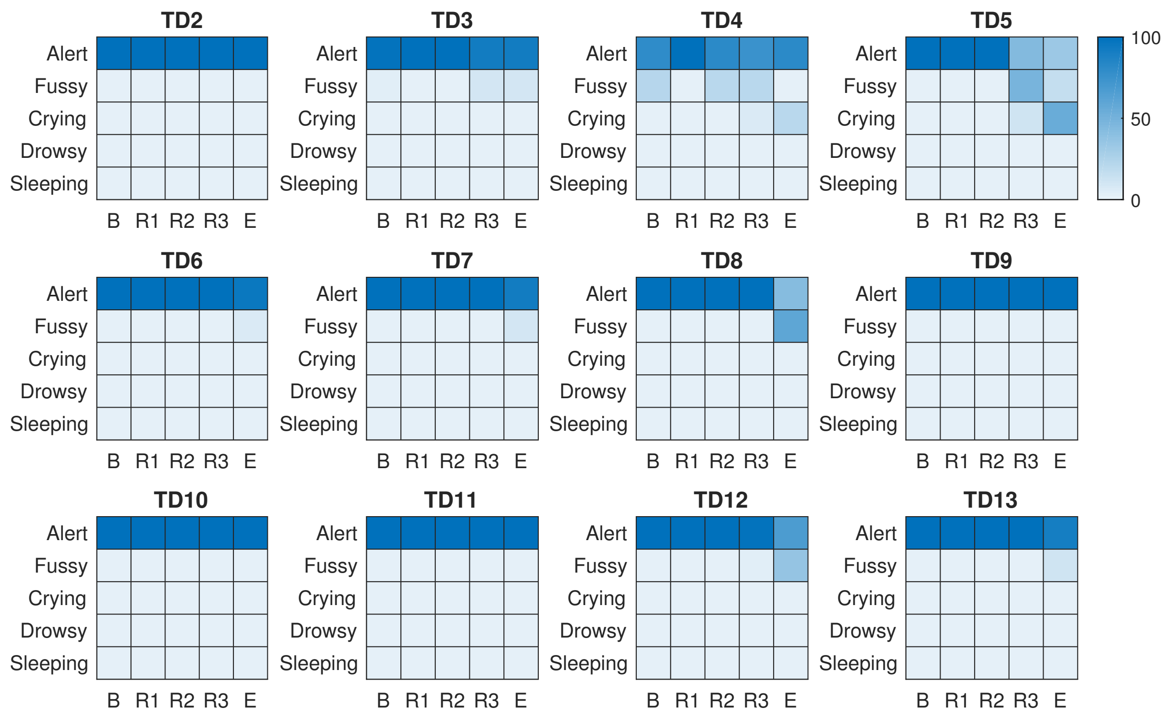


Fig. 6. Behavioral states of each participant across the different study phases. In the x-axis labels, B is the baseline, R1 is the movement reward, R2 is the movement and lights reward, R3 is the movement and sound reward, and E is the extinction phase.

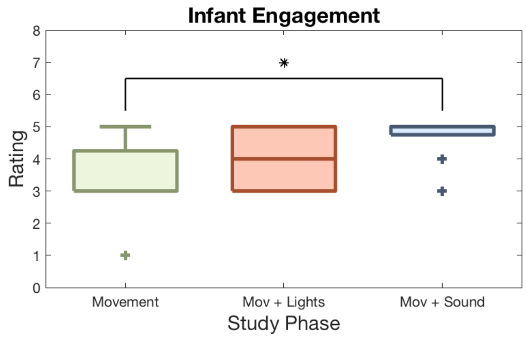
the study period.

The behavioral state results support our decision to use data from the baseline phase for our contingency learning threshold. We used a one-way rANOVA with an $\alpha = 0.05$ significance level to evaluate differences in the frequency of the identified infant behavioral states across study phases. In cases where significant differences were found, post hoc Tukey multiple comparisons tests revealed which pairs of conditions had statistically significant differences. These tests showed differences in the percentage of time that infants were alert across phases ($F(4,44) = 4.25$, $p = 0.005$, $\eta = 0.198$). As is also evident in the raw data, infants were significantly more alert during the baseline, movement reward, and movement and lights reward than during the extinction phase. Infants also tended to be most fussy during the extinction phase, which could indicate that they learned the contingency and became disappointed by the cessation of robot responses, or that the study lasted too long and infants became fussy, among other interpretations.

D. Parent Surveys

Parent evaluation of the study events revealed differences in the perception of the reward conditions. Because the surveys were administered on paper, occasional survey completion errors or omissions led to differences in how many responses we received (as indicated in the reported F scores and in Table IV). Overall, we received eight or more responses to each question.

Each parent was asked to answer questions about the emotional state, motion, engagement, imitation tendencies,



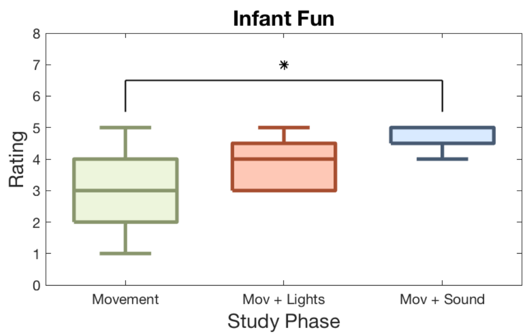


Fig. 7. Parents' ratings of the infants' engagement and fun levels during each reward condition. The center box lines represent the median; the box edges are the 25th and 75th percentiles. The whiskers show the range up to 1.5 times the interquartile range, and outliers are marked with a "+". Brackets indicate significant differences as determined by the post hoc multiple comparisons test.

and enjoyment of their infant during interactions with the robot overall. Additional questions assessed the infant's experience with mobiles, the family's perceptions of and experiences with robotics, and the family's interest in participating in future studies. The mean and standard deviation of parent responses to each question appear in Table IV. The responses indicate that parent opinions of the challenge level of the study activity were positive. Parents generally thought the infants were happy, excited, successful, and engaged throughout the interaction with the robot. The ratings of infant motion levels and imitation levels were closer to neutral, but still above the neutral rating on average.

Each parent also shared their perceptions of the infant's engagement and level of fun during each reward. Using a one-way rANOVA with an α = 0.05 significance level, we observed differences in parent perceptions of infant engagement level ($F(2,18) = 3.87$, $p = 0.042$, $\eta = 0.233$) and fun level ($F(2,16) = 7.74$, $p = 0.005$, $\eta = 0.375$) across reward conditions. As shown in Fig. 7, post hoc Tukey multiple comparisons tests showed that parents found the movement and sound reward to be more engaging and fun for their infants than the reward involving motion alone.

V. Discussion

The study results enable us to evaluate our hypotheses about how infants respond to robot contingent rewards, whether infants imitate humanoid robots, and how parents perceive the infant-robot interaction.

A. Hypothesis Testing

The results of our study support **H1**; the majority of the infants learned the contingency presented by the robot, as evaluated using benchmarks from past contingent learning research (not involving robots). A statistical test of differences similarly revealed that infants moved above the acceleration threshold significantly more in all reward phases as compared to the baseline phase when the robot was stationary. This result supports our use of precedents in contingency learning as one essential component of our infant-robot interaction design and evaluation. The knowledge that contingent rewards from a robot can encourage infants to move more than they normally would is an essential building block for infant-robot SAR studies.

Infant behaviors during the study provide some support for **H2**. Our analysis showed that nine of the twelve infants behaved in a way that fulfilled our definition of imitation during at least one reward phase. Changes in infant behavior over the course of the different reward phases could be due to external factors like learning or fatigue. This result supports the idea that infants may be trying to imitate the NAO robot, although more research is necessary to further test the imitation hypothesis.

Parent perceptions support some of the additional understanding described in **H3**. Although parent perceptions of which reward motivated their children to move most did not perfectly match the top rewards suggested by the contingency learning results, parents did perceive that their infants were moving slightly more than normal. Parents' perceptions of the interaction overall were very positive. This is important for the promise of SAR adoption for infant interventions. Additionally, parents were happy with the challenge level of the activity, which may indicate that the difficulty of the study design was appropriate for the participant population. Another encouraging note was that parents positively perceived socially assistive robots although none of them had prior experience with robots.

B. Major Strengths and Limitations

A major contribution of this research is that it introduces SAR into a new and potentially high-impact domain: teaching and reinforcing infant motion. Although studies involving infants can be challenging due to a variety of factors, we were able to recruit the targeted number of participants for this work. The infants were engaged by the robot and remained alert for the vast majority of the interaction time. The results of this first study in socially assistive infant-robot interaction suggest that infants can learn robot-delivered contingent rewards and may try to imitate a robot.

The designed SAR system can be used to deliver a variety of rewards for a nuanced range of infant motions

TABLE IV

PARENT RESPONSES TO ADDITIONAL SURVEY QUESTIONS FROM THE POST-STUDY ASSESSMENT.

Question	# Recorded Responses	Response Mean	Response Standard Dev	Lower Anchor Point	Upper Anchor Point
How happy or unhappy do you think your baby felt? (SAM valence images)	10	4.00	0.82	Unhappy	Happy
How calm or excited do you think your baby felt? (SAM arousal images)	10	3.60	0.70	Calm	Excited
How controlled or controlling do you think your baby felt? (SAM dominance images)	10	3.60	0.70	Controlled	Controlling
Do you think your baby learned what he/she had to do?	10	3.80	0.79	Never	Always
Do you think your baby moved more than he/she typically does?	10	3.30	1.25	Never	Always
Do you think your baby was engaged/focused on the robot?	10	4.00	0.94	Never	Always
Do you think your baby was mimicking the robot?	9	3.44	0.88	Never	Always
Do you think your baby enjoyed the activity?	9	4.11	0.60	Never	Always
Would you change the difficulty of the activity in a potential future session?	9	3.00	0.00	Much Lower	Much Higher
How often does your baby play with a mobile?	9	1.89	1.17	Never	Always
Do you think social robotics can be useful to improve the well-being of babies?	9	4.11	1.05	Never	Always
Have you ever had any previous experience with social robots?	9	1.00	0.00	Never	Always
Would you participate in potential studies related to infant-robot interaction?	9	4.56	0.53	Never	Always

and interventions. As discussed in Section II, the robot's physical embodiment and ability to provide a variety of reward types help it to motivate infants and hold their attention for longer than other therapeutic tools. The infant-like size and humanoid anatomy of the robot also allow it to fit in the infant's visual field and demonstrate motions that an infant can imitate. This observation, combined with other study results, provides us with novel insights that will inform future targeted SAR interventions for infants.

Because this data collection involved very young infants, we needed to limit the session duration to minimize the possibility of infant stress or fatigue. We were also limited in the number of conditions we could include in the experimental design; additional types of demonstrations and rewards could help us to learn more about how to teach and reinforce infant motion. The $9,000 cost of the NAO robot is high, but this price is competitive with medical equipment and the robot is more dexterous and versatile than past contingency learning tools like mobiles or toys. Our software architecture is also designed to allow for the replacement of the NAO robot with a more cost-effective alternative when one becomes available. Finally, our study involved a single-session design in a laboratory setting. In the future, data gathered in a natural environment over a longer interaction period will further inform our work on SAR for infants and increase the potential benefit of SAR-based infant interventions.

C. Key Contributions and Future Work

The results of this work further the general understanding of infant-robot interactions and build the foundation for the new research area of using SAR to teach and reinforce infant motion. In this work, we focused on 6- to 8-month-old infants' responses to a small humanoid robot. Specifically, we investigated how much infants produced leg movement above an acceleration threshold when being rewarded by robot behaviors, whether infants imitated the robot's ball kick motion, and how parents perceived the infant-robot interactions. We found that the majority of the infants learned the contingency. Most infants also imitated the robot in at least one of the reward phases. Parent opinions of the robot were generally high, although their perceptions of infant motion levels and imitation of the robot were only slightly above neutral. Future work will build on these findings to develop more adaptive and personalized robot behaviors for teaching and motivating infant movement.

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