

# Learning limb-specific contingencies in early infancy

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## Abstract

Most research with the mobile paradigm has the underlying assumption that young infants can selectively move the limb causing the contingent feedback from the mobile while avoiding irrelevant motor responses. Contrary to this long-held belief, others have argued that such differentiation ability is not fully developed early in life. In the current study, we revisited the traditional mobile paradigm with a contemporary research approach (using high-precision motion capture techniques, a yoked-control design, and a large sample size) to investigate whether response differentiation ability emerges before 5 months of age. The data collected from 76 infants (aged between 115 and 159 days) revealed that infants can learn sensorimotor contingencies by increasing the movement of the connected leg relative to their baseline level. However, they did not differentially increase the movement of the leg causing an effect in the environment compared with that of other limbs. Our results illustrate that response differentiation ability emerges later than previously suggested.

## 1 | INTRODUCTION

Dynamic interactions between the body and the world are a constant in human development. The infant's systematic exploration of sensorimotor contingencies is an important aspect of these interactions (Jacquey, Fagard, et al., 2020). One of the most well-known paradigms that has been used to study how infants learn and remember sensorimotor contingencies is the mobile paradigm (Rovee &

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Rovee, 1969; Rovee-Collier et al., 1978; for a review see Sen & Gredebäck, 2021), in which a mobile is connected to one of the infant's legs in such a way that moving the leg causes movement of the mobile. Rovee-Collier et al. (1978) used this paradigm to assess 3-month-old infants' ability to selectively move the connected leg in order to move the mobile. That is, they asked whether young infants can learn a new motor behavior (increasing the movement of the limb/s connected to the mobile) while avoiding unnecessary actions that do not cause any change in the environment (movement of the limb/s i.e., not connected to the mobile). They reported that 3-month-old infants increased the movement rate of the connected leg relative to the other as well as the movement rate of the lower body relative to the upper body, pointing to a response differentiation ability in early infancy (Rovee-Collier et al., 1978; Rovee-Collier & Gekoski, 1979). This finding has provided an important validation of the mobile paradigm (Sen & Gredebäck, 2021) because it suggested that sensorimotor learning in this paradigm was not a joy reaction where the infant responds with excitement by means of increasing the movement of all limbs (Piaget, 1952). Rather, they can adapt to the environment's demands in an efficient way by increasing their movement (Rovee-Collier, 1996; Rovee-Collier & Gekoski, 1979). Furthermore, it inspired contemporary researchers to better understand the developmental underpinnings of response differentiation ability (Heathcock et al., 2005; Jacquey, Popescu, et al., 2020; Watanabe & Taga, 2006, 2009; Zaadnoordijk et al., 2018, 2020). Nevertheless, small sample sizes (4–13 infants/group) and inferences made without statistical analysis (e.g., “Because of the robustness of the phenomenon, no formal analysis of the reversal phase was undertaken.”; Rovee-Collier et al., 1978, p. 330) highlight some of the methodological limitations of the original article, especially given modern contemporary research practices. Most critically, the more recent literature that has assessed this issue is strongly divided. Some studies provide support for the claim that 3-month-old infants' body representation, proprioception, and motor abilities are sufficiently sophisticated for response differentiation (Angulo-Kinzler & Horn, 2001; Heathcock et al., 2005; Thelen, 1994), while other paradigms and recent findings suggest that response differentiation ability emerges much later in development (Hoffmann et al., 2017; Jacquey, Popescu, et al., 2020; Watanabe & Taga, 2006). At this moment, we do not know whether response differentiation between the legs can be observed in infants under 5 months of age. The aim of the present study is to revisit the original paradigm used by Rovee-Collier and colleagues, this time with the addition of high-precision motion capture techniques, appropriate statistical procedures, a yoked-control design, and a much larger sample size. But before this, let us take a closer look at the literature that has created this knowledge gap.

A broad and diverse set of studies suggests that young infants' actions can be tuned to task demands and environmental constraints. In fact, detecting sensorimotor contingencies (i.e., the ability when an action is associated with an outcome that could be either perceptual or proprioceptive, Jacquey, Fagard, et al., 2020) has been considered fundamental for the development of various abilities such as goal-directed motor behavior (Corbetta & Thelen, 1996; Corbetta et al., 2019; Delafield-Butt & Gangopadhyay, 2013), motor control (Fagard et al., 2018), sense of agency (Rochat, 1998; Rochat & Morgan, 1995; Zaadnoordijk et al., 2018), and social understanding (Marshall & Meltzoff, 2015). The development of action control that is sensitive to sensorimotor contingencies begins to form in the womb and diversifies in the postnatal period. For instance, movements that provide contingent proprioceptive feedback (e.g., hand to eye, hand to mouth) are present in the womb (Fagard et al., 2018; Kurjak et al., 2004; Piontelli, 2010; Rochat, 1993) and often interpreted as both anticipatory and goal-directed (Reissland & Austen, 2019; Reissland et al., 2014; Zoia et al., 2007). In the first months of life, young infants have been demonstrated to manifest a sensitivity to both temporal (Bahrick & Watson, 1985; Filippetti et al., 2013) and visuo-spatial congruencies (Begum Ali et al., 2021; Filippetti et al., 2015; Rochat & Morgan, 1995; Schmuckler & Fairhall, 2001; Watson, 1979). For instance, newborns systematically bring their hands under a beam of light so that they can maintain contingent

proprioceptive and visual information (van der Meer et al., 1995; van der Meer 1997). Three months of age, infants can detect the contingent relationship between self-produced leg movements and the video of them (Bahrick & Watson, 1985; Rochat & Morgan, 1995).

To date, there have been few studies that support the claim that response differentiation ability is observed in infants younger than 4 months of age (Heathcock et al., 2005; Thelen, 1994). For instance, newborns changed the position of their hands to keep them visible under the light while their unseen hands in the dark remained stationary (van der Meer, 1997). Thelen (1994) created a novel task context for 3-month-old infants where their legs were yoked together with a piece of elastic, making simultaneous movement of the legs more efficient in terms of activating the mobile. The results demonstrated that young infants overcame their tendency for alternate kicking (the more prominent movement strategy at this age) and learned a hard-to-produce movement pattern (simultaneous movement) in their legs to receive self-produced contingent feedback from the mobile. Similarly, when a motor task required 3-month-old infants to develop task-specific motor solutions for the legs (i.e., adjusting the angle between upper and lower leg), they changed their kicking behavior in a way that maintained the visual feedback from the overhead mobile (Angulo-Kinzler et al., 2002; Angulo-Kinzler & Horn, 2001). Collectively, these studies suggested that spontaneous motor behavior can be tuned to the demands of the task and environment from very early on (Thelen & Corbetta, 2002). Response differentiation ability (Rovee-Collier et al., 1978) can be seen as an example of such adaptive behavior, enabling the infant to explore learning strategies in which only efficient motor behaviors are exercised.

At the same time, contradictory to the findings noted above, a number of recent studies show that response differentiation ability might not be fully developed at 3 months of age (Somogyi et al., 2018; Watanabe & Taga, 2006, 2009; Zaadnoordijk et al., 2020). Watanabe and Taga (2009) showed that 3-month-old infants had undifferentiated movement patterns for their legs while they learned to move the mobile. Up until 4 months of age, infants increased the movement of all limbs both as a response to contingent visual stimulation (Watanabe & Taga, 2006) and to noncontingent tactile stimulation (Somogyi et al., 2018). Response differentiation ability in the arms in the presence of contingent visual feedback seems to begin emerging at 4 months of age (Jacquey, Popescu, et al., 2020; Watanabe & Taga, 2006). For the legs, increased movement rates for the stimulated leg were observed only from 5 months of age (Hoffmann et al., 2017). In line with these findings, it was argued that detection of sensorimotor contingencies follows a cephalocaudal trend (Somogyi et al., 2018; Thomas et al., 2015). According to this view, motor organization of the upper body parts (e.g., face, trunk) is considered to be more mature early in development while responsiveness in the lower body (e.g., legs, feet) emerges later.

## 1.1 | Present study

Due to the contrasting evidence in the literature, it remains unclear if young infants are able to differentially learn that actions with one leg, but not the other, cause an effect in the world, and adjust their leg kicking accordingly. The present study was designed to revisit the original suggestion by Rovee-Collier et al. (1978) and to shed light on whether response differentiation for the lower body exists before 5 months of age, as suggested by their earlier work. Given the current crisis of replicability in science (Fanelli et al., 2017; Ioannidis, 2005, 2008, 2018) and more specifically in developmental research (Frank et al., 2017), it is of utmost importance to revisit the findings that were put forward decades ago, with contemporary statistical and methodological methods. In doing so, researchers could differentiate true findings from false positives and build new knowledge on a more solid ground.

To this end, we conducted a traditional mobile paradigm study where infants moved the mobile with a particular leg and received contingent visual feedback as a result of their kicking, using high-precision motion capture methods and a yoked control design. Our aims were twofold. First, we

attempted to replicate the finding that infants increase their leg movement relative to baseline while they learn the contingent relationship between their actions and the consequences of these actions. Second, we investigated whether response differentiation ability (more kicking with the connected leg than with other limbs) exists early in infancy. We targeted infants who were 4.5 months old, an age about which studies differ substantially regarding infants' abilities: either they have the ability to learn the contingency and identify the limb causing the effect in the environment or they still lack response differentiation ability, a finding that goes contrary to the assumptions postulated by the classical studies using the mobile paradigm (Heathcock et al., 2005; Rovee-Collier et al., 1978).

## 2 | METHOD

### 2.1 | Participants

The final sample consisted of 76 (35 males) infants aged between 115 and 159 days ( $M = 134.6$  days,  $SD = 10.8$  days). These infants were evenly divided into experimental ( $M = 134.9$  days,  $SD = 10.8$  days) and yoked control groups ( $M = 134.3$  days,  $SD = 11.1$  days). Thirty-six additional infants participated in the experiment but were taken out of the final sample. Reasons for exclusion were fussiness (23; 14 infants in experimental group, 9 infants in control group), technical error (5), and failure to attend to the task (8; 6 infants in experimental group, 2 infants in control group). Failure to attend to the task involved situations in which the infant fell asleep, played with other limbs or sensor cables for several minutes, was in an inactive state (e.g., not moving). In addition, data from two infants were not used in the analysis because the data of the infants that they were paired with were excluded due to technical error (i.e., the data file was saved in an incorrect format). In exchange for their participation, parents received a gift card worth 100 SEK that could be used in a local bookstore. The present study was conducted according to guidelines laid down in the Declaration of Helsinki, with written informed consent obtained from a parent or guardian for each child before any assessment or data collection. All procedures involving human subjects in this study were approved by the Swedish Ethical Review Agency at Uppsala University.

### 2.2 | Materials

All experimental sessions took place at the (blind for review). Each infant was tested in a crib in which the walls were draped with a white linen cloth to prevent any visual distraction. There were three mobile stands attached to the walls of the crib (see Figure 1). One of them was placed at the head of the crib and the other two were mounted on the sidewalls, facing each other. The ribbons hanging from the side stands were used to tie the infant's right and left leg. The purpose of these stands was to create the same tactile stimulation on the right leg as on the left leg, created by the ribbons attached to the stands. The mobile was always hooked to the left-leg stand, referred to as the contingent stand from here onwards, for the contingent phase of the experiment (*acquisition*). The mobile stand placed at the head of the crib, hereafter referred to as the noncontingent stand, was used to attach the mobile during the noncontingent phases (*baseline & extinction*).

The mobile consisted of six animal-shaped stuffed toys to which small bells were directly attached to provide auditory stimulation. The mobile was always suspended approximately 30 cm above the infant's torso. Depending on the experimental phase, the mobile was either hooked to the contingent (*acquisition*) or noncontingent stand (*baseline & extinction*). The session was filmed by a video camera from an overhead view.



**FIGURE 1** The experimental set-up. Here in the picture, the mobile is hooked to the contingent stand (i.e., left-leg stand). During non-contingent phases (i.e., baseline and extinction for the experimental group; baseline, acquisition and extinction for the yoked-control group), the mobile was hooked to the mobile stand placed at the head of the crib

Kinematic data were recorded in real time with an electromagnetic position-tracking device (Ascension Technology Corporation) with a sampling rate of 60 Hz. Five cylindrical sensors (2.0 mm diameter) were connected to an electronic unit with white cables (1.2 mm diameter) and were used to track the position of each limb and the mobile. Four limb sensors were attached to cotton cuffs worn on the infant's wrists and ankles while the fifth sensor was sewed to the central toy of the mobile. The sensors sampled the location of each limb and the mobile in the  $x$ ,  $y$ , and  $z$  coordinates. Consistent with the previous literature that used advanced kinematic measurement techniques in the mobile paradigm (Watanabe & Taga, 2006, 2009), we chose velocity level as a proxy for limb movements. The velocity calculation was based on the displacement in each coordinate in a given time interval. As a dependent variable, overall velocity was calculated by using the following formula:

$$\sqrt{V_x^2 + V_y^2 + V_z^2}$$

### 2.3 | Procedure

There were two conditions: experimental and yoked control. In both conditions, the procedures for noncontingent phases (baseline and extinction) were identical. Conditions differed in terms of the procedure of the acquisition phase. In the acquisition phase of the experimental condition, the infant's left leg was connected to the mobile, creating the sensorimotor contingency. Consistent with the previous literature on the mobile paradigm (Fagen et al., 1984; Rovee & Rovee, 1969; Rovee-Collier et al., 1978), there was no counterbalancing between the legs. This was further motivated by prior work suggesting that infants, at this age, do not yet demonstrate a lateral leg preference (Thelen et al., 1983). In the yoked control condition, such contingency did not exist; instead, the mobile was moved by the experimenter at a distance through a ribbon connected to the noncontingent stand. The

rate of this visual stimulation was determined by the movement of the mobile in the acquisition phase of the paired infant in the experimental group. The experimenter manipulated the mobile via an additional ribbon to produce non-contingent feedback for the control group, similar to what has been done in prior mobile paradigm studies (McKirdy & Rovee, 1978; Rovee & Rovee, 1969; Rovee-Collier et al., 1978, 1981). However, it is important to note that exact details of this procedure (e.g., how experimenters quantified the amount of movement in the mobile produced by the infant) were not mentioned in these studies. What was different in the present study was that the velocity trajectory of the mobile for each infant in the experimental condition was plotted and used in creating the visual stimulation for the paired infant in the yoked control group. The experimenter moved the mobile at a rate that was as identical as possible to the yoked infant's (experimental group) movement rate in the acquisition phase of the experiment (the graph demonstrating the movement profile of the mobile in experimental group and yoked control group is available at <https://osf.io/PU7KJ>, as Supplemental Figure 4).

The experimental session consisted of three phases in total: baseline (3 min), acquisition (9 min), and extinction (3 min). The length of each phase was the same as in the classical mobile paradigm studies (Rovee & Fagen, 1976; Rovee-Collier et al., 1981, 1985). In these studies, the same 15-min experimental procedure was repeated on consecutive days, while single 15-min session was used in the present study. Depending on the phase of the experiment, the mobile was hooked either to the noncontingent stand (baseline and extinction) or to the contingent stand (acquisition) by the experimenter. The beginning of each condition was marked by the experimenter on the data by using a trigger button. Although baseline and extinction phases were procedurally the same, they had different purposes. The baseline phase measured the average velocity level of the infant. In the extinction phase it was observed how the infant reacted to either the absence of sensorimotor contingency, or the absence of noncontingent visual stimulation, previously presented in the acquisition phase, depending on the condition (i.e., experimental and yoked control, respectively). It is important to note that the experimenter was not blind to the study hypothesis while creating the non-contingent feedback for the yoked-control group.

After arriving in the laboratory, the parent was informed that the study was designed to investigate how infants understand the relationship between their motor behavior and what happens in their immediate environment. After the parent provided the informed consent, the experiment started with placing the infant supine in the crib. The cotton cuffs that the limb sensors were attached to were put on the infant's wrists and ankles. The parent and experimenter always stayed out of sight, except when the experimenter positioned the mobile in the corresponding stand (i.e., the noncontingent or contingent stand), in the time between different phases of experiment. If the infant became fussy and cried continuously for more than a minute at any phase of the experiment or the parent decided to end the experiment, the session was terminated and the infant was excluded from the final sample (23 infants were excluded for this reason). If continuous crying for at least 1 min occurred within the last 2 min of the experiment (i.e., the last 2 min of the extinction phase), the experiment was terminated to avoid the further distress of the infant but the infant was kept in the final sample.

## 2.4 | Data preparation

First, the data of each participant were segmented by condition (baseline, acquisition, and extinction) after removing the data points outside of the markers that determined the beginning and end of each condition. During the binning procedure (i.e., grouping the velocity values into 1-min units for each participant for each phase of the experimental session), the velocity data for each limb was averaged

over each minute of the experimental session. We used 1-min bins for pooling of motor activity as this was also the temporal resolution used by Rovee-Collier et al. (1978) to investigate response differentiation. The baseline and extinction conditions had three bins representing 3 min while the acquisition phase had nine bins representing 9 min. The missing (e.g., not applicable) values were excluded during the calculation of the mean velocity values. Missing values constituted 0.1% of all data points, with a mean of 50.92 and standard deviation of 31.87 cases across different participants in the sample. Finally, the individual observations (i.e., participant velocity level) of the experimental and yoked control groups were gathered separately in summary statistics form (the mean for each bin) to create the aggregated data for further statistical analysis. We analyzed and visualized the aggregated data by using R (v3.6.1; R Core Team, 2019). Bayesian analysis was conducted in JASP (JASP Team, 2019). The raw data and the code for data processing and analysis are available at <https://osf.io/PU7KJ>. Visual inspection of the quantile plots and the Shapiro-Wilk test were used to test the normality assumption while the homoscedasticity assumption was assessed with Levene's test. Outliers were assessed by the box-plot method. If the normality assumption was satisfied by an outlier treatment, the extreme outliers (i.e., values above the third quartile + 3 IQR or below the first quartile - 3 IQR) were replaced by the next lower value. Following that, an appropriate parametric test (e.g., *t* test) was implemented. However, if the normality assumption was still violated even after an outlier treatment, the original data were subjected to either the nonparametric equivalent of the statistical test (e.g., Wilcoxon signed-rank test) or a robust statistical method. In addition, the data was analyzed by using Bayesian equivalent of the above-mentioned frequentist tests when the frequentist analysis revealed null results for the effect of interest. Bayesian analysis is commonly used to provide evidence in favor of the null findings and can quantify the strength of the evidence supporting the null hypothesis (van Doorn et al., 2021). As recommended by Lee and Wagenmakers (2013), a classification scheme was used to determine the strength of the evidence in Bayesian analysis.

### 3 | RESULTS

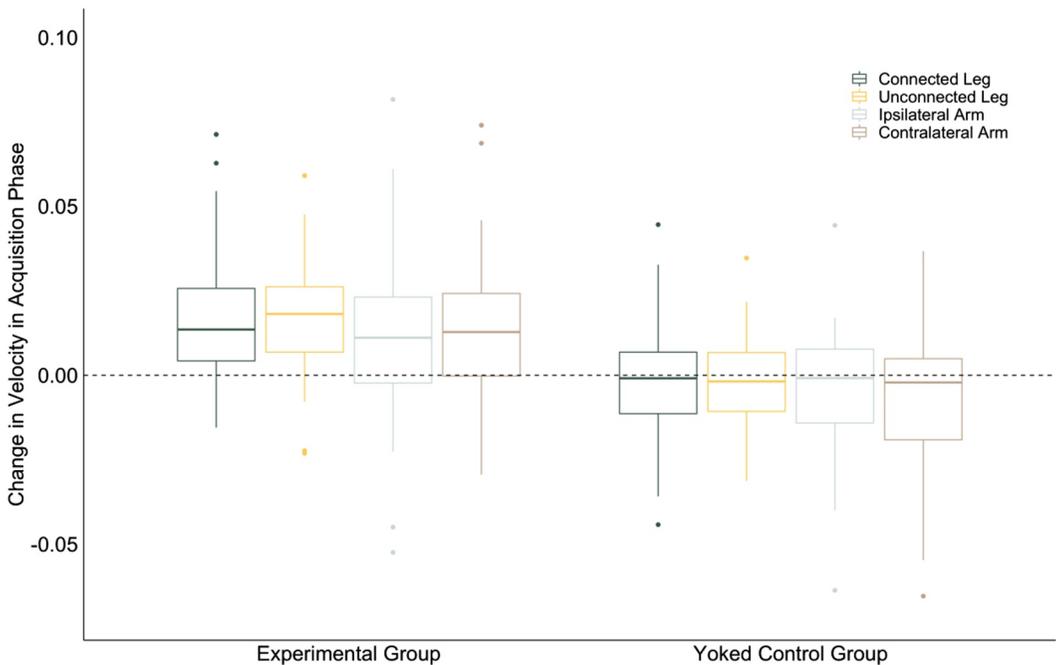
Descriptive statistics (the mean and standard deviation of velocity) for the experimental and yoked control group across three different phases of the experiment are shown in Table 1.

As shown in Figure 2, the change in velocity (i.e., the amount of change in velocity levels from baseline to acquisition phase) in the connected leg was higher in the experimental group ( $M = 0.02$ ,  $SD = 0.03$ ) than in the yoked control group ( $M = -0.01$ ,  $SD = 0.02$ ). To check for normality assumption, Shapiro-Wilk test was performed and did not show evidence of non-normality for control group ( $W = 0.98$ ,  $p = .77$ ). However, the distribution of velocity in the connected leg for experimental group departed significantly from normality ( $W = 0.87$ ,  $p < .01$ ). Based on this outcome, a non-parametric

TABLE 1 Velocity levels by condition and different phases of experiment

Limb	Experimental			Yoked control		
	Baseline	Acquisition	Extinction	Baseline	Acquisition	Extinction
Connected leg	0.043 (0.028)	0.063 (0.035)	0.063 (0.032)	0.038 (0.021)	0.037 (0.018)	0.046 (0.025)
Unconnected leg	0.049 (0.033)	0.072 (0.035)	0.068 (0.033)	0.041 (0.025)	0.040 (0.021)	0.051 (0.024)
Ipsilateral arm	0.039 (0.028)	0.050 (0.027)	0.048 (0.022)	0.031 (0.021)	0.028 (0.015)	0.038 (0.022)
Contralateral arm	0.045 (0.026)	0.061 (0.039)	0.056 (0.030)	0.041 (0.025)	0.033 (0.017)	0.045 (0.022)

Note: This table presents the mean (standard deviation) of velocity levels (i.e., mean velocity) across conditions (experimental and yoked control) and different phases of the experiment (baseline, acquisition, and extinction).

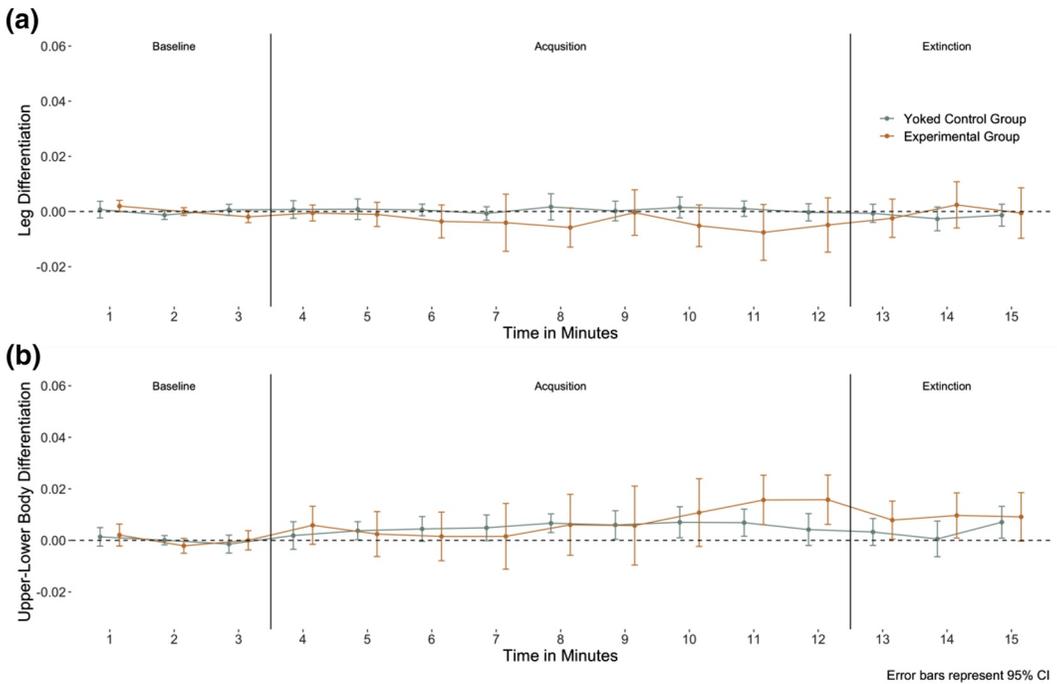


**FIGURE 2** Change in velocity (i.e., baseline-corrected velocity values of all limbs calculated by subtracting average velocity value of baseline from acquisition phase) in the acquisition phase of the experiment. Dashed line refers to the fact that there is no difference between the baseline and acquisition levels

test was used. A Wilcoxon signed-rank test indicated that the difference between experimental group and control group was statistically significant ( $p < .001$ , effect size  $r = 0.86$ ). We conducted a post-hoc power analysis with the program G\*Power (Erdfeider et al., 1996) to find out whether the study had enough power to detect expected effect. The power to detect an effect of this size was determined to be 0.99, critical  $t(71) = 1.99$ .

A two-way ANOVA was conducted to investigate the effects of condition (experimental and yoked control) and limb type (connected leg, unconnected leg, ipsilateral arm, contralateral arm) on baseline-corrected velocity values (i.e., the average velocity value of the baseline being subtracted from the velocity values in each bin of all phases) in the acquisition phase. Shapiro-Wilk test was used to check for normality assumption (see Supplemental Table 2 for its results, <https://osf.io/PU7KJ>). Levene's test showed that the variances for baseline-corrected velocity values were equal,  $F(7, 296) = 1.13$ ,  $p = .34$ . Neither normality nor equality of variances assumptions were violated. Results of a two-way ANOVA showed that there was a statistically significant main effect of condition on change in velocity during the acquisition phase (see Figure 3),  $F(1, 296) = 64.08$ ,  $p < .001$ ,  $\eta^2 = 0.18$ . Neither the main effect of limb type nor that of interaction was significant,  $F(3, 296) = 1.76$ ,  $p = .154$ ,  $\eta^2 = 0.02$  and  $F(3, 296) = 0.52$ ,  $p = .669$ ,  $\eta^2 = 0.01$ , respectively.

We performed a Bayesian mixed-model analysis of variance (ANOVA) to test the null hypothesis that neither the main effect of limb type nor its interaction with condition affected change in velocity. Models involving the main effect of limb type and interaction between limb type and condition were compared to the models not involving these factors. Bayes factors quantifying the extent to which the data supported the exclusion of factor limb type and its interaction with condition were  $BF_{01} = 0.73$  (anecdotal evidence) and  $BF_{01} = 2.97$  (anecdotal evidence), respectively. Therefore, it can be concluded from the Bayesian analysis that there is anecdotal evidence against the inclusion of



**FIGURE 3** Response differentiation between connected-unconnected leg (Figure 3a) and upper-lower body (Figure 3b) for the experimental and yoked control groups over successive minutes of the experimental session. Leg differentiation refers to response differentiation between the legs and it was calculated by subtracting baseline-corrected velocity value of the unconnected leg from that of the connected leg for each minute of the experimental session (9 min in total). Response differentiation between upper and lower body parts was calculated by subtracting the baseline-corrected velocity value of the upper body (the mean velocity of the arms) from that of the lower body (the mean velocity of the legs) for each minute of the experimental session. Dashed line refers to the fact that there is no difference between the baseline and acquisition velocity levels

limb type factor. To put it differently, observing the present data given the model that did not involve limb type and its interaction with condition was more likely (0.73 times and 2.97 times, respectively) compared to observing the present data given the model consisting both limb type and its interaction with condition.

In order to test the differentiation between the connected and unconnected leg (i.e., response differentiation between the legs) over the course of the acquisition phase, the baseline-corrected velocity value of the unconnected leg was subtracted from that of the connected leg for each minute of the experimental session (9 min in total). Shapiro-Wilk test was conducted to check for normality assumption (see Supplemental Table 3 for the results, <https://osf.io/PU7KJ>). Levene's test demonstrated that the variances for baseline-corrected velocity values weren't equal,  $F(17,666) = 3.21, p < .001$ . As a result, assumptions of normality and the equality of variances were both violated and a robust mixed-design ANOVA (Mair & Wilcox, 2020) based on trimmed means was implemented. The data on response differentiation between the legs are presented in Figure 3a. Results revealed that there was no main effect of condition,  $F(1, 34.05) = 3.24, p = .081$ , or time,  $F(8, 28.98) = 1.30, p = .281$ . The interaction effect was also not significant,  $F(8, 28.98) = 1.49, p = .121$ .

We performed Bayesian mixed model analysis of variance (ANOVA) to show that neither the main effect of condition nor its interaction with time impacted response differentiation between the legs. Models that included the main effect of condition and the interaction between condition and

time were compared with models that did not include these factors. Bayesian factors measuring the extent to which data supported the exclusion of factor condition and its interaction with the time were  $BF_{01} = 3.82$  (moderate evidence) and  $BF_{01} = 93.25$  (very strong evidence), respectively. It can be concluded that condition (experimental and yoked control groups) did not affect response differentiation between the legs. In other words, to observe the present data given the model that did not involve condition and its interaction with time was more likely (3.82 times and 93.25 times, respectively) compared to the model consisting both condition and its interaction with time.

In order to examine the response differentiation between upper (i.e., arms) and lower (i.e., legs) body during the acquisition phase, the mean velocity values of the arms and legs were calculated separately. Response differentiation between upper and lower body parts was determined by subtracting the baseline-corrected velocity value of the upper body (the mean velocity of the arms) from that of the lower body (the mean velocity of the legs) for each minute of the experimental session. To check for normality, Shapiro-Wilk test was conducted (see Supplemental Table 4 for the results, <https://osf.io/PU7KJ>). In addition to normality assumption, equality of variances assumption was also violated,  $F(17,666) = 4.85$ ,  $p < .001$ . Hence, a robust mixed-design ANOVA was conducted. As illustrated in Figure 3b, there was no main effect of condition or time,  $F(1, 33.47) = 0.609$ ,  $p = .441$ , and  $F(8, 28.60) = 1.13$ ,  $p = .372$ , respectively. The interaction effect was also not significant,  $F(8, 28.60) = 1.92$ ,  $p = .096$ .

Bayesian mixed model analysis of variance (ANOVA) was conducted to show that neither the main effect of condition nor its interaction with time influenced response differentiation between upper and lower body. Bayesian factors measuring the extent to which the data supported the exclusion of factor condition and its interaction with time were  $BF_{01} = 4.74$  (moderate evidence) and  $BF_{01} = 7.69$  (moderate evidence), respectively. Hence, there was moderate evidence against the hypothesis that experimental and yoked control groups differed from each other in response differentiation between upper and lower body. In other words, to observe the present data given the model that did not involve condition and its interaction with time was more likely (4.74 times and 7.69 times, respectively) compared to the model consisting both condition and its interaction with time.

## 4 | DISCUSSION

In the present research, we investigated 4.5-month-old infants' ability to learn sensorimotor contingencies in the traditional mobile paradigm experimental procedure (i.e., where the infant's leg is connected to an overhead mobile to provide contingent feedback). While some hypothesize that young infants' sophisticated body representation, proprioception, and motor abilities allow them to narrow contingent responses to a particular limb (Angulo-Kinzler & Horn, 2001; Heathcock et al., 2005; Rovee-Collier et al., 1978; Thelen, 1994), others have claimed that response differentiation ability is not fully developed early in life (Hoffmann et al., 2017; Somogyi et al., 2018; Watanabe & Taga, 2006, 2009). In the current study, we addressed the lack of general agreement in the literature by asking two questions. Can young infants learn sensorimotor contingencies in the mobile paradigm? If they so, can response differentiation (i.e., differentiating leg movements by avoiding actions irrelevant to the task) be observed?

First, we investigated whether infants increased their movement rate relative to the baseline as a response to contingent feedback from the overhead mobile while infants who were provided with noncontingent visual feedback during the acquisition phase maintained their baseline movement rate. Our results suggest that infants can learn the contingency between their leg movement and the movement of the overhead mobile. More specifically, we replicated the original finding (Rovee &

Rovee, 1969) where more movement increase in the connected leg was observed in the experimental group compared with the control group presented with noncontingent visual stimulus. From this result, we can infer that the increase in the movement rate of the connected leg was not merely a response to visual stimulation in the environment but rather a behavioral manifestation of a learned sensorimotor contingency. This finding is consistent with extant literature claiming that young infants increase their kicking rate when their leg is connected to the overhead mobile, suggesting that they learn how to move the mobile (Rovee & Rovee, 1969; Rovee-Collier et al., 1978). It is important to note that there have been some reports on replication failures of the learning effect in the mobile paradigm (Jacquey, Fagard, et al., 2020) and wide variability in how many infants can learn sensorimotor contingencies in a given sample (Jacquey, Fagard, et al., 2020; Sen & Gredebäck, 2021). The present study, being one of the first attempts to revisit this original finding with modern contemporary research practices (e.g., high-precision motion capture techniques, a yoked-control design, a large sample size), has thus provided further support for young infants' ability to learn sensorimotor contingencies in the mobile paradigm. Furthermore, current results were obtained without using any learning criteria (e.g., selecting the infants who increased their movement in the acquisition phase relative to their baseline and exclude the ones who did not satisfy the criteria) that was a common methodological practice in the mobile paradigm literature (e.g., Rovee-Collier et al., 1985; Tiernan & Angulo-Barroso, 2008; Watanabe & Taga, 2006, 2009). This study shows that learning effect (i.e., learning sensorimotor contingencies) in the mobile paradigm holds with a sample size larger than previous mobile paradigm studies (e.g., five or six infants per group, Sen & Gredebäck, 2021) and more critically without selecting a group of infants who fulfill a particular behavioral criterion (i.e., learning criteria).

Second, we investigated whether infants increased the movement of the connected leg more than that of other limbs, which would indicate a response differentiation ability (i.e., ability to learn specific contingent relations between the movement of the leg and the mobile). The results demonstrate that this was not the case, suggesting that infants did not differentially increase the movement of the leg connected to the mobile compared with that of the other limbs, and this trend did not differ between the experimental and yoked control groups. This finding may be somewhat limited by the fact that the evidence provided by Bayesian analysis in favor of the null hypothesis (no difference between the limbs) is anecdotal (i.e., in a scale from no evidence to extreme evidence, anecdotal evidence comes right after no evidence and it is considered not very strong, for the Bayesian classification scheme used in the present study see, Lee & Wagenmakers, 2013). In addition to the velocity difference between the limbs, we also examined how response differentiation ability (i.e., the differentiation between the two legs and the differentiation between the upper and lower body) unfolds during the learning process. However, we did not find any significant main effects here either. Consistent with the design used by Rovee-Collier et al. (1978), both legs were tied with ribbons (i.e., one was connected to the mobile and the other was connected to the empty stand) in the present study to match proprioceptive feedback in both legs. One limitation of this methodological choice could be that connected leg might have received additional tactile stimulation due to the mobile's movement. Such tactile stimulation could have been a factor facilitating response differentiation by increasing the perceptual saliency of the connected leg that does not exist in unconnected leg. However, our results pointed to the opposite. Despite possible contribution of such perceptual saliency, no response differentiation was observed in the present sample. In line with these results, Bayesian analysis moderately supported the null hypothesis that condition (experimental or control group) did not have any impact on either leg or body differentiation. To put it differently, there is moderate support in favor of the hypothesis that infants did not show any response differentiation competency in the mobile paradigm.

Present results differ from previous research providing evidence in favor of response differentiation between the legs at 3 months of age (Heathcock et al., 2005; Rovee-Collier et al., 1978). This

inconsistency might be attributed to the experimental setting. In fact, both Rovee-Collier et al. (1978) and Heathcock et al. (2005) tested infants in their home cribs while present study took place in the laboratory which might have resulted in infants being more responsive at their home. However, lack of response differentiation in the current sample can't be explained by this factor alone because learning effect (i.e., increase in the movement during acquisition phase relative to the baseline) was successfully replicated even though the testing was done in the laboratory. Another factor that distinguishes present results from the previous ones (i.e., supporting response differentiation ability) could be related to when and how response differentiation was observed during the experimental session. For instance, in the Rovee-Collier et al. (1978) study, response differentiation was present first time during the extinction phase following 15 min of the acquisition phase. Recent research showed that a movement burst can be occasionally observed in the extinction phase due to the violation of cause and effect relationship established in the acquisition (Zaadnoordijk et al., 2018, 2020). Therefore, it is possible that absence of contingency during the extinction might have facilitated response differentiation by further motivating infants to make the mobile move again. Future work could investigate whether changing conditions in the environment, particularly going from a responsive to an unresponsive environment (i.e., from receiving constant contingent feedback to absence of contingency) facilitates response differentiation.

In addition, learning sessions were longer and spread over consecutive days in the Rovee-Collier et al. (1978) and Heathcock et al. (2005) studies (i.e., total duration of the learning sessions reached up to 30–40 min). Ruling out the possibility that learning duration wasn't sufficiently long for response differentiation might be out of the scope in the present study. Nevertheless, it is important to note that learning duration of the studies that observed response differentiation in the upper body (e.g., arm-differentiation, Jacquey, Popescu, et al., 2020; Watanabe & Taga, 2006) was limited to only a few minutes. This might suggest that when the infants have the behavioral competency for response differentiation, a couple of minutes of exposure to sensorimotor contingency is sufficient for them to manifest such ability. Therefore, lack of response differentiation in the present study suggests that young infants are *not* able to differentially learn contingent actions with one leg that causes an effect in the world while avoiding irrelevant motor behavior (i.e., movement of the unconnected leg or arms) in the mobile paradigm. Our results are in line with Watanabe and Taga (2009), demonstrating that response differentiation between the legs is not observed at 3 months. Similar to Watanabe and Taga (2009), the present study benefited from contemporary research practices (e.g., high-precision motion capture techniques, a large sample size) that could explain why our results were in contrast with earlier findings of the mobile paradigm. To sum up, we can conclude that infants learn that there is a contingency between their actions and the world, but they move all limbs in order to further enact this causal relation. Their actions increase due to the contingency, but across the entire body.

Recent research suggested that development of body representations begins during the prenatal period and continues throughout the first years of life (Bremner & Spence, 2017; Milh et al., 2007; Zoia et al., 2007). Both spontaneous movements and self-touch play a critical role in the formation of the body schema (Hoffmann, 2017; Hoffmann et al., 2017). Previous research pointed to a developmental process in which these spontaneous motor behaviors that are irrelevant to the task demands (e.g., movement of the nonacting hand while shaking a rattle, movement of the arm not connected to the mobile) become less frequent as infants get older (D'Souza et al., 2017; Kato et al., 2013; Somogyi et al., 2018; Watanabe & Taga, 2006). For instance, Watanabe and Taga (2006) showed that infants increased the activity of all limbs as a response to contingent feedback from the mobile at 2 months, while differentially increasing the movement of the particular limb (i.e., arm) was observed at 4 months. It might be that infants in the present study behaved in a manner similar to the 2-month-old group in Watanabe and Taga (2006) study by increasing the activity of all limbs because they had not yet developed the

ability to avoid extraneous motor behaviors, particularly of the lower body. We suggest three possible explanations for why the development of response differentiation ability unfolds differently for arms and legs. First, it might be that the differentiation ability emerges later for the lower compared with the upper body parts. We know from the previous research that the ability to detect vibrotactile stimulation follows a cephalocaudal trend (i.e., the localization of stimulated areas on the upper body is more pronounced earlier in development; Somogyi et al., 2018; Thomas et al., 2015). This might be explained by infants having more experience with arm-based contingencies compared to leg-based contingencies in the first months of life. Second, lack of visual input from the lower body while infants interact with the mobile in a supine position might make response differentiation between the legs more arduous for young infants. Previous research suggested that as infants look at their hands while interacting with an object, they perform task-irrelevant actions less frequently because attention directed towards the manipulating hand facilitates inhibition of extraneous motor behaviors (Soska et al., 2011). An interesting avenue for future research might be investigating whether the availability of visual cues from the lower body could assist response differentiation, particularly for the infants who have not yet developed such ability. This inquiry could also provide a deeper understanding about the mechanisms underlying the development of response differentiation in early infancy. Lastly, actions involving leg movements would require whole-body movements (e.g., using both arms and legs for locomotion) while using single arm is more common due to its function for reaching and grasping. This could be seen as another explanation for the distinctive developmental trajectories for arm and leg differentiation.

In conclusion, the current study makes two important contributions to the literature. First, it revisits the original mobile paradigm with contemporary research techniques and provides supporting evidence for young infants' ability to learn sensorimotor contingencies. Second, it confirms that response differentiation ability emerges later than previously suggested by Rovee-Collier et al. (1978) and Heathcock et al. (2005).

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## DATA AVAILABILITY STATEMENT

All data and supplemental material have been made publicly available at Open Science Framework (OSF) and can be accessed at <https://osf.io/PU7KJ>.

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