

Video Article

Quantifying Learning in Young Infants: Tracking Leg Actions During a Discovery-learning Task

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Abstract

Task-specific actions emerge from spontaneous movement during infancy. It has been proposed that task-specific actions emerge through a discovery-learning process. Here a method is described in which 3-4 month old infants learn a task by discovery and their leg movements are captured to quantify the learning process. This discovery-learning task uses an infant activated mobile that rotates and plays music based on specified leg action of infants. Supine infants activate the mobile by moving their feet vertically across a virtual threshold. This paradigm is unique in that as infants independently discover that their leg actions activate the mobile, the infants' leg movements are tracked using a motion capture system allowing for the quantification of the learning process. Specifically, learning is quantified in terms of the duration of mobile activation, the position variance of the end effectors (feet) that activate the mobile, changes in hip-knee coordination patterns, and changes in hip and knee muscle torque. This information describes infant exploration and exploitation at the interplay of person and environmental constraints that support task-specific action. Subsequent research using this method can investigate how specific impairments of different populations of infants at risk for movement disorders influence the discovery-learning process for task-specific action.

Video Link

The video component of this article can be found at <https://www.jove.com/video/52841/>

Introduction

Task-specific actions emerge from spontaneous movements during infancy. It has been proposed that task-specific actions emerge through a discovery-learning process^{1,2}. Tasks are discovered by infants as they spontaneously move and explore actions which produce novel effects in the environment. Task-specific actions emerge as infants exploit the connections between their actions and their effects on the world around them. However, little is known about the precise processes that infants explore and exploit to learn to modify their spontaneous movements to perform task-specific actions. Here a method is described in which 3-4 month old infants learn a task by discovery and their leg movements are captured to quantify the learning process.



Figure 1: Infant kicking-activated mobile task. The center light-emitting diode (LED) attached to the rigid body of each foot (yellow circle) activates the mobile when it crosses the virtual threshold (red dashed line). Re-printed with permission from Sargent *et al.*³

This discovery-learning task uses an infant activated mobile that rotates and plays music based on the specified leg action of infants³. Infants placed supine under the mobile activate it by moving their feet vertically across a virtual threshold (**Figure 1**). This paradigm is unique in that as

infants independently discover that their leg actions activate the mobile, the infants' leg movements are tracked using a motion capture system allowing for the quantification of the learning process.

The experimental protocol includes two days of data collection. Day 1 consists of a 2 min baseline condition in which an infant kicks spontaneously but his leg actions cannot activate the infant mobile, followed by a 6 min acquisition condition in which the infant's leg actions activate the infant mobile if the infant moves his feet vertically to cross a virtual threshold. This protocol allows for the quantification of infants' spontaneous leg actions as well as the quantification of various aspects of the movements as infants explore the relation between their leg actions and activation of the infant mobile. On Day 2, in addition to the 2 min baseline condition and 6 min acquisition condition, a 2 min extinction condition is added in which the infant's leg actions do not activate the infant mobile. This allows for the quantification of how infants change their leg actions when an already learned environmental response is discontinued.

In previous infant mobile paradigms, frequency of leg movement^{4,6}, specific hip and knee angles^{7,8}, or kicking a panel⁹ have been reinforced with mobile movement. Performance each day was defined as an increase in these leg actions during the acquisition or extinction condition as compared to the baseline condition^{4,9}. Learning across days was defined as an increase in these leg actions during the baseline or acquisition condition of Days 2 or 3 and the baseline condition of Day 1^{5,6}. These previous mobile paradigms demonstrate that infants increase the frequency of leg actions that are reinforced with mobile activation, however, they do not provide information on the movement options infants have available to them when learning the task. For example, if kicking rate is reinforced, infants demonstrate performance and learning when their kicking rate increases either when interacting with the mobile or when the mobile no longer activates. This demonstrates that infants can refine their kicking rate, but it is unknown if infants can refine their leg coordination pattern or torque production to generate leg actions that are not within their preferred movement repertoire.

This mobile paradigm is unique in that infants are required to demonstrate more refined leg action to activate the mobile than in previous mobile paradigms. In this mobile paradigm, the height of each foot above the table is computed during the 2 min baseline condition using position data from a light emitting diode (LED) attached to each foot. A virtual threshold is then set parallel to the table at a height that is within the upper range of the height of both feet during the baseline condition. During acquisition, the mobile rotates and plays music if either foot crosses the threshold. After 3 sec, the mobile stops and reactivates only if the infant moves the foot below the threshold, and then moves the foot vertically and again crosses the threshold. To activate the mobile for the greatest amount of time, infants need to move a foot above the threshold and maintain it against gravity for 3 sec, then quickly move the foot below the threshold and again move it above the threshold and hold it there for 3 sec, etc. This requires more refined leg action than simply increasing kicking rate.

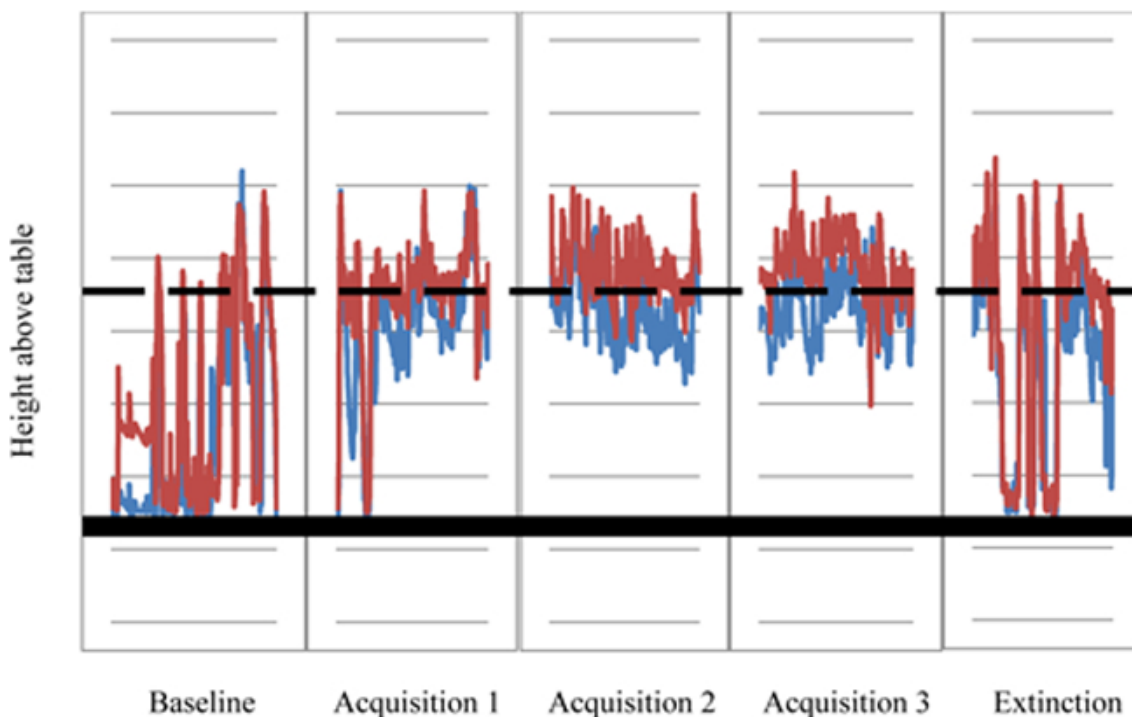


Figure 2: Unfiltered position data of end effectors (feet) from a representative infant. Unfiltered position data from Day 2 of a 3 month old infant who demonstrated learning based on the individual learning criteria. The red line is position data of the z-coordinate of the light-emitting diode (LED) placed on the right foot. The blue line is position data from the LED on the left foot. Thick black line is the table. Dotted line is the virtual threshold placed 14 cm above the table as individually determined for each infant based on the height of their kicking during baseline condition of Day 1. X-axis is time labeled by 2 min intervals. Note how the infant moves his feet during baseline when the mobile does not activate and during the first 30 sec of acquisition 1, then he consistently keeps both feet off the table and moves his feet right around the threshold for the next 5½ min until the mobile no longer activates during the extinction condition.

The second unique feature of this mobile paradigm is that each infant's leg action is tracked using state-of-the-art motion capture techniques to quantify how infants use their movement options to learn the task. Unfiltered position data of the LED on each foot that activates the mobile from one representative infant is included in **Figure 2**. Note how the infant moves his feet at various heights above the table during baseline and the

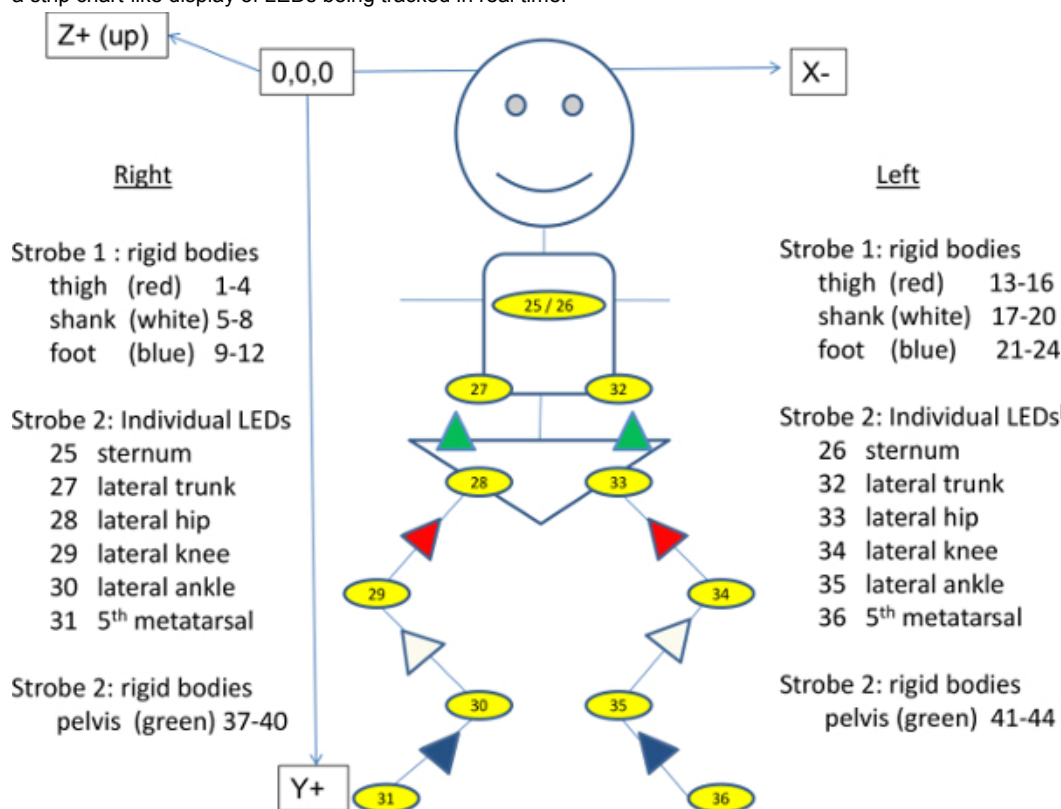
first part of acquisition, but then moves both feet right around the threshold during the rest of the acquisition condition until the mobile no longer activates during extinction. This is one of many potential movement strategies to accomplish the discovery-learning task. The strategies can be quantified by computing three-dimensional kinematics and kinetics using position data acquired from the motion capture system. Specifically, the learning process is quantified in terms of the percentage of reinforced leg action (%RLA), which is equal to the duration of mobile activation, position variance of the end effectors (feet) which activate the mobile, hip-knee coordination patterns, and hip and knee joint torques.

Protocol

The Institutional Review Board at the University of Southern California approved this study.

1. System Preparation

- Set up the motion capture system. Please note: these steps are different for each motion capture system.
 - Align the coordinate systems of the two motion capture sensors to that of one sensor by clicking "Perform New Registration" in the motion capture program, entering a collection time of 30 sec, clicking "Register," and moving the registration object within the capture volume for 30 sec. When registration is successfully completed, observe a root mean square (RMS) registration error on the computer screen.
 - Align the global coordinate system to the testing table using the registration object by clicking "Perform New Alignment" in the motion capture program.
 - Define the origin by placing the registration object on the upper right corner of the testing table and clicking "Digitize" in the motion capture program. Define the Z-axis by placing the registration object on top of a box and clicking "Digitize"; the Z-axis is perpendicular to the table.
 - Define the Z/Y+ plane by moving the registration object on the box along the length of the table and clicking "Digitize"; the Y-axis is parallel to the length of the table and the X-axis is parallel to the width of the table.
- Plug the LEDs into the two strobe ports and enter the number of LEDs per strobe port within the motion capture system program (24 for strobe port 1 and 20 for strobe port 2). Refer to **Figure 3** for the number and location of each LED. Select missing data view to provide a strip chart-like display of LEDs being tracked in real time.



LEDs. Strobe 1 consists of the rigid bodies (4 LEDs on each rigid body) for the right and left thigh, shank, and foot. Strobe 2 consists of the rigid bodies for the right and left pelvis, the sternum markers, and the individual LEDs.

- Set up the infant mobile computer program.
 - Input the number of minutes for each condition. For Day 1, input 2 for phase 1 (2 min baseline, non-reinforcement condition), 6 for phase 2 (6 min acquisition, reinforcement condition), and 0 for phase 3 (0 min extinction, non-reinforcement condition).
 - For Day 2, input 2 for phase 1 (baseline), 6 for phase 2 (acquisition), 2 for phase 3 (extinction), and check "Use Zmin as Default" so that the threshold computed during baseline of Day1 will be the threshold used for the acquisition condition of Day 2.

3. Choose "*StreamframesAllFrames*" and click "*Send*" to enable the mobile program to use data from the motion capture system to activate the infant mobile based on specified criteria.
3. Set up the video cameras.
 1. Initiate the video computer program for the three synchronized videos (right lateral, left lateral, overhead views).
 2. Start the additional video camera over the infant's head to record facial expressions and eye gaze.

2. Infant Preparation

1. Describe the experiment to the parents and inform them to interact as little as possible with their infant.
NOTE: Tell the parents that if the infant does not become fussy throughout the experiment, the parents should sit beside the infant outside of their view, however, if the infant becomes fussy there is a progression of interaction with the infant.
 1. First, ask the parent to say, "Everything is okay, I'm right here," in a reassuring tone.
 2. Second, ask the parent to stand in the infant's view while reassuring the infant.
 3. Third, ask the parent to either hold one of the infant's hands or give the infant a pacifier.
 NOTE: The least amount of parent interaction necessary to keep the infant calm and alert is given and is ended as quickly as possible.
2. Undress the infant, place the infant under the infant mobile, and secure the infant to the table using a Velcro band placed across the trunk.
3. After the infant is secured to the table, place the sternum markers and pelvic, thigh, shank, and foot rigid bodies on the infant.

3. Infant Mobile Learning Task

1. Each day, initiate the mobile learning task by synchronously starting the motion capture system, mobile computer program, and video cameras.
 1. On both days from min 0 to 2, the baseline condition, observe the infant spontaneously kicking.
 2. On Day 1 during the 2 min baseline condition, observe as the infant mobile program continuously computes the threshold for mobile activation based on the z-data from one of the LEDs on the rigid body of each foot. Example, marker 9 on the right foot and marker 21 on the left foot. Marker 9 is the center LED on the right foot rigid body circled in yellow in **Figure 1**. Marker 21 is the center LED on the left foot rigid body.
 3. At the end of the 2 min baseline, the mobile program will set the threshold at a height of one standard deviation (SD) above the average height of both feet during the 2 min baseline condition.
 4. On both days from min 2 to 8, the acquisition condition, observe as the infant mobile rotates and plays music when the LED placed on either foot crosses the threshold computed during the 2 min baseline condition of Day 1.
NOTE: Mobile activation will continue for as long as the foot is above the virtual threshold to a maximum of 3 sec. After 3 sec, the mobile will reactivate only if the infant moves the foot below the virtual threshold, and then moves the foot vertically and again crosses the threshold. This "3 sec rule" encourages active leg exploratory movements versus holding the feet above the threshold.
 5. On Day 2 from min 8-10, the extinction condition, observe as the infant kicks spontaneously without mobile reinforcement.
2. After the infant interacts with the mobile, collect a static calibration trial to define a local coordinate system for each leg segment and define a reference configuration for each body segment in space.
 1. Fix ten individual LEDs bilaterally to the infant's skin using double-sided EKG collars at the following locations: lateral midline of the trunk below the tenth rib, greater trochanter of the hip, lateral knee joint line, ankle lateral malleolus, and distal end of the 5th metatarsal.
 2. Hold the infant's lower extremity in an extended, anatomical position for 5 sec. All joint angles in this calibration position are defined as 0°.
3. On Day 2, collect anthropometric data.
 1. Weigh each infant on a digital electric scale.
 2. Take the following measurements: total length of the infant; circumference at mid-segment of thigh, shank, and foot; width of knee (at the knee joint line), ankle (at the malleoli), and foot (at the metatarsal heads); and length of the thigh (greater trochanter to knee joint line), shank (knee joint line to lateral malleolus), and foot (medial malleolus to first metatarsophalangeal joint).

4. Data Analysis

1. Analyze performance and learning by computing the %RLA during each 2 min interval of the experiment using a custom computing language program such as Matlab. Compute the duration of time one or both of the LEDs on each foot that activated the mobile were above the threshold. Since the mobile does not activate after an interval of 3 sec, subtract the duration of time in which one or both LEDs were above the threshold for greater than a 3 sec interval.
 1. Measure performance of the group each day by statistically analyzing whether the %RLA during any one of the three, 2 min acquisition intervals significantly exceeds the 2 min baseline interval^{3,4,7,9,10}.
 2. Categorize individual infants as having performed the task each day if the %RLA during any one 2 min acquisition interval is equal to or greater than 1.5 times the %RLA in the 2 min baseline interval^{3,4,6,9,10}.
 3. Measure learning of the group across days by determining *statistically* whether the %RLA during the entire 6 min acquisition condition Day 2 exceeds the %RLA during the baseline condition Day 1^{3,6}.
 4. Categorize individual infants as Learners if the %RLA during the entire 6 min acquisition condition of Day 2 is equal to or greater than 1.5 times the baseline condition of Day 1^{3,6,11}.

2. Analyze arousal and attention by coding videotapes during each 2 min interval of the experiment. The arousal scale is defined as: drowsy = 1, alert and inactive = 2, alert and active = 3, fussy = 4, and crying = 5^{3,8,11}. The attention scale is defined as: 0 = not looking at the mobile, 1 = looking at the mobile^{3,8}.
3. Process position data and extract kicks using custom Matlab programs.
 1. Load position data files outputted from the motion capture system into a custom Matlab program to interpolate missing position data (maximum of 20 consecutive frames) using a cubic spline.
 2. Load the interpolated files into a custom Matlab program to (a) filter position data using a fourth-order Butterworth with a cut-off frequency of 5 Hz as determined from power spectrum analysis, and (b) compute the following joint angles: hip flexion/extension, hip abduction/adduction, hip external/internal rotation, knee flexion/extension, ankle inversion/eversion, ankle dorsiflexion/plantarflexion as described in¹².
 3. Load the angle files into a custom Matlab program to extract kicks. Define the beginning of a kick as the onset of a continuous leg movement in which the hip or knee joint angle change exceeded 11.5° (0.2 radians) into either flexion or extension^{3,9,13-15}. Define the end of the kick as the frame of peak extension following a flexion movement or peak flexion following an extension movement^{3,9,14}.
4. For all kicks, compute kinematic parameters using custom Matlab programs.
 1. Compute position variance in the z-direction (vertical, task-specific direction) of the LED on each foot that activated the mobile³.
 2. Compute hip flexion/extension and knee flexion/extension joint correlations using Pearson correlation coefficients (*r*) at zero lag between hip and knee joint angle excursions. To compare correlations (*r*) among infants, convert hip-knee joint angle correlations to Fisher Z scores^{3,9,15}.
 3. Time-normalize the joint angle data, then compute hip flexion/extension and knee flexion/extension continuous relative phase (CRP) from the angular position/velocity data^{16,17}. Analyze the results of the CRP computation at the following five time points: (a) beginning of kick, (b) peak velocity of the first segment, (c) joint reversal, (d) peak velocity of the second segment, and (e) end of kick³.
5. For all kicks, identify non-contact kicks by viewing the synchronous video data. Compute kinetic parameters for non-contact kicks using custom Matlab programs.
 1. Compute the segmental mass and center-of-mass from equations modified for infants from Hatze's anthropometric model for adults¹⁸. Compute the 3D moments of inertia of the thigh, shank, and foot segments from equations modified for infants from Jensen's anthropometric model for adults¹⁹.
 2. Calculate the terms in the following equation of motion using the screw theory of spatial manipulations²⁰.

$$M(\theta)\ddot{\theta} + C(\theta, \dot{\theta})\dot{\theta} + N(\theta) = T \in \mathbb{R}^6(1)$$

is derived using the Lagrangian approach, where $M(\theta)$ is the inertia matrix, $C(\theta, \dot{\theta})$ the Coriolis and centrifugal torque matrix, $N(\theta)$ the gravitational (GRA) torques and T the muscle (MUS) torques.
 3. Compute joint torques using the 3D kinematic data from the non-contact kicks, body-segment inertial parameters, and the biomechanical equation of motion.
 4. Partition the net (NET) torque at each joint into motion-dependent (MDT), GRA, and MUS torque contributions²¹. NET torque is directly proportional to the accelerations at each joint. MDT torque is related to the passive torques associated with mechanical interactions among the moving interconnected segments of the limb. GRA torque is related to the passive force of gravity acting downward on the limb. MUS torque includes forces from active muscle contractions and passive deformations of muscles, tendons, ligaments, and other periarticular tissues.
 5. For the hip and knee separately, compute torque impulse as the magnitude of the contribution of each partitioned torque (MUS, GRA, MDT) to NET torque. Compute the positive or negative torque impulse (torque * time) during intervals in which the knee MUS torque acted in the same or opposite direction compared with the knee NET torque. Perform this same computation with knee GRA and MDT torques and hip MUS, GRA, and MDT torques. For the hip and knee separately, sum all positive and negative impulses for each torque component to yield a measure of the magnitude of the contribution of each partitioned torque impulse (MUS, GRA, MDT) to NET torque impulse.

Representative Results

The learning process of young infants can be quantified in terms of the %RLA, position variance of the end effectors (feet), hip-knee angle correlation coefficients, and hip and knee joint torques. Each level of analysis provides unique information about how infants explore the relation between their leg actions and activation of the infant mobile during the discovery-learning process.

For the statistical analysis of %RLA and hip-knee angle correlation coefficients, mixed regression models with an autoregressive covariance structure and group (Learners, Non-learners) as the between-subject factor were used to test the differences of each dependent variable (%RLA, hip-knee correlation coefficient) among baseline, acquisition, and extinction conditions across days. For the statistical analysis of hip and knee muscle torque impulse within the Learner group, mixed regression models with an autoregressive covariance structure were used for each dependent variable (hip muscle torque impulse, knee muscle torque impulse) among baseline, acquisition, and extinction conditions across days. Statistical analyses were completed using SAS (version 7.0, SAS Institute Inc.) with alpha level set at 0.05 for overall F values and adjusted using a Bonferroni correction for preplanned post hoc comparisons.

Percentage of Reinforced Leg Action

Percentage of reinforced leg action is assessed to determine whether infants have performed and learned the task³. To depict typical differences in %RLA between 3-4 month old infants who learn and do not learn the task, 20 infants were separated into Learners (*n* = 8) and Non-learners (*n* = 12) based on an individual learning criterion. The Learners, but not Non-learners, significantly increased %RLA between the Day 2 acquisition condition and the Day 1 baseline condition (*p* < 0.001, **Figure 4**). Graphing the results in 2 min increments provides information about the time course of the learning process. Note the initial decrease in Learner's %RLA during the first 2 min of the Day 1 acquisition condition. Infants who

learned the task decreased their overall action when the infant mobile began to activate, perhaps first as an orienting response, then perhaps as a strategy to determine whether their actions were associated with mobile activation.

Position Variance of the End Effectors

The position variance of the end effectors (feet) provides information on the strategy used by infants to accomplish the task. It also provides insight into what was “learned” by the infant. Learners demonstrate one of two strategies to accomplish this discovery-learning task. When interacting with the mobile, if the threshold is high, over 50% of the infant’s leg length above the table (14-20 cm), Learners ($n = 2$) decrease variance of their feet in the vertical, task-specific direction by moving close to the threshold (**Figure 5**). They appear to have learned the location of the threshold. If the threshold is low, less than 50% of the infant’s leg length above the table (5-8 cm), Learners ($n = 6$) increase variance of their feet in the vertical direction by moving their feet progressively higher (**Figure 6**). They appear to have learned to kick high. It would be expected that with additional days, Learners with a low threshold would learn the minimum height necessary to activate the mobile and their position variance in the vertical direction would decrease.

Hip-Knee Angle Correlation Coefficients

To depict differences in hip-knee coordination patterns, 20 infants were separated into Learners ($n = 8$; 5,055 kicks analyzed) and Non-Learners ($n = 12$; 8,240 kicks analyzed) based on an individual learning criterion. The Learners, but not Non-learners, significantly decreased their hip-knee angle correlation coefficient between the Day 2 acquisition condition and the Day 1 baseline condition ($p < 0.001$, **Figure 7**). This coordination change was also found in the relative phase results (**Table 1**). Learners demonstrated less in-phase hip-knee coordination when interacting with the mobile, perhaps because this coordination pattern provided a more efficient means to activate the mobile. When the height is low, the most efficient means to activate the mobile may be to flex and extend the hip while maintaining the knee extended. When the height is high, the most efficient way to activate the mobile may be to maintain the hip flexed and flex and extend the knee. Either strategy results in more out-of-phase hip-knee coordination (hip flexes while knee extends) as compared to an infant’s typical kicking pattern of nearly synchronous flexion and extension of the hip and knee.

Hip and Knee Muscle Torque Impulse Contribution to Net Torque Impulse

Hip and knee MUS torque impulse of the Learners ($n = 8$; 917 kicks) is graphed in **Figure 8**. Learners significantly increased hip MUS torque impulse contribution to hip NET torque impulse between the Day 2 extinction conditions and all other conditions ($p < 0.001$). Learners also increased knee MUS torque impulse contribution to NET knee torque impulse between the Day 2 extinction conditions and all other conditions except Day 1 baseline ($p < 0.001$). It was expected that there would be a decrease in hip and knee MUS torque impulse between the Day 2 acquisition condition and the Day 1 baseline condition since it was hypothesized that Learners were using the less in-phase hip-knee coordination pattern because it was more efficient than a more in-phase coordination pattern. This change in MUS torque impulse may not have been demonstrated because to compute accurate torques, only kicks that do not contact the surface or the other leg can be used. Only 917 kicks met this criterion, versus the 5,055 kicks used to document the decrease in hip-knee correlation coefficients during the Day 2 acquisition condition. Therefore, the decrease in the number of kicks analyzed, although necessary to accurately compute the torques, may have contributed to the non-significant difference in MUS torques between the baseline and acquisition conditions. However, a robust finding was the increase in hip and knee MUS torque impulse during the extinction condition. Infants who had learned the task appeared to be generating large hip and knee MUS torques during the extinction condition in an attempt to reactivate the mobile.

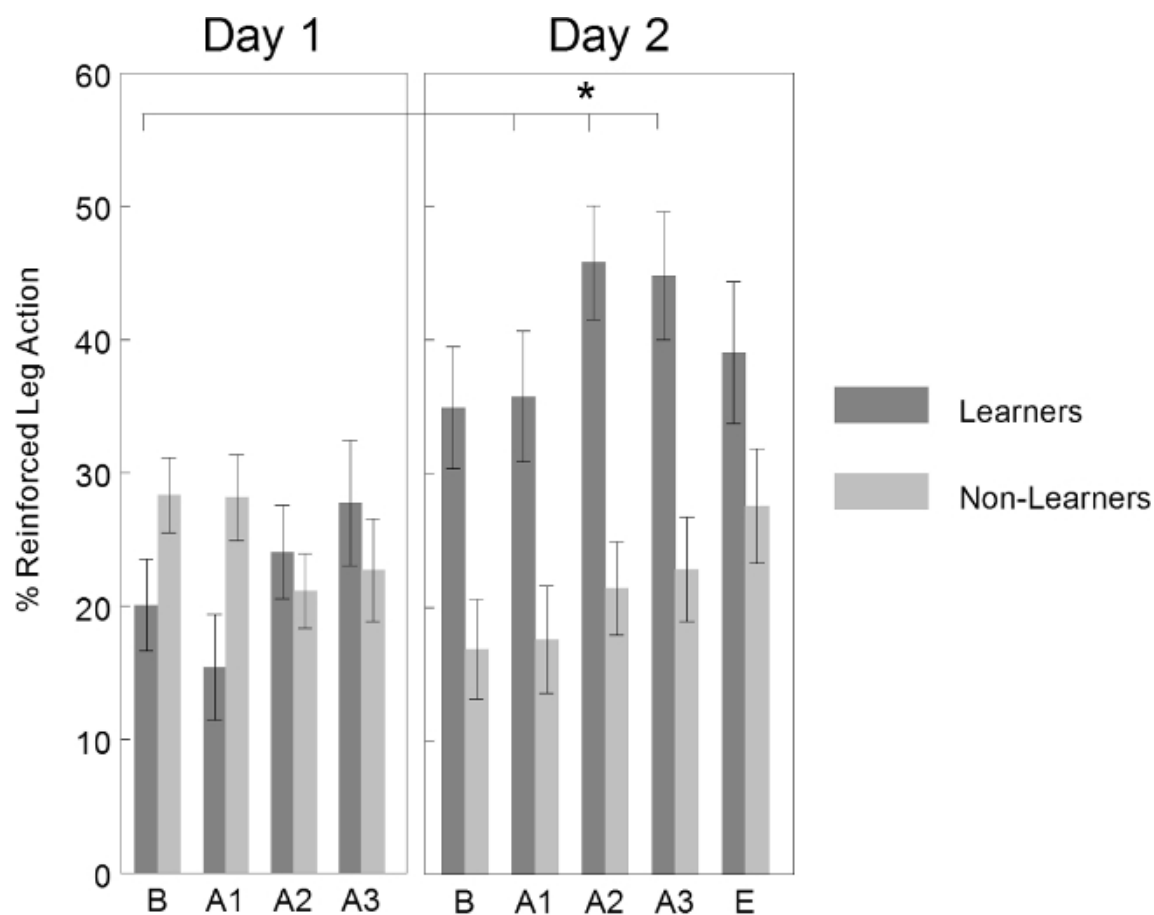


Figure 4: Mean percentage of reinforced leg action by 2 min interval. Infants were separated into Learners ($n = 8$) and Non-learners ($n = 12$) based on an individual learning criteria. Learners significantly increased percentage of reinforced leg action between the Day 2 acquisition condition and the Day 1 baseline condition (adjusted $p < 0.001$). B = baseline, A = acquisition, E = extinction.

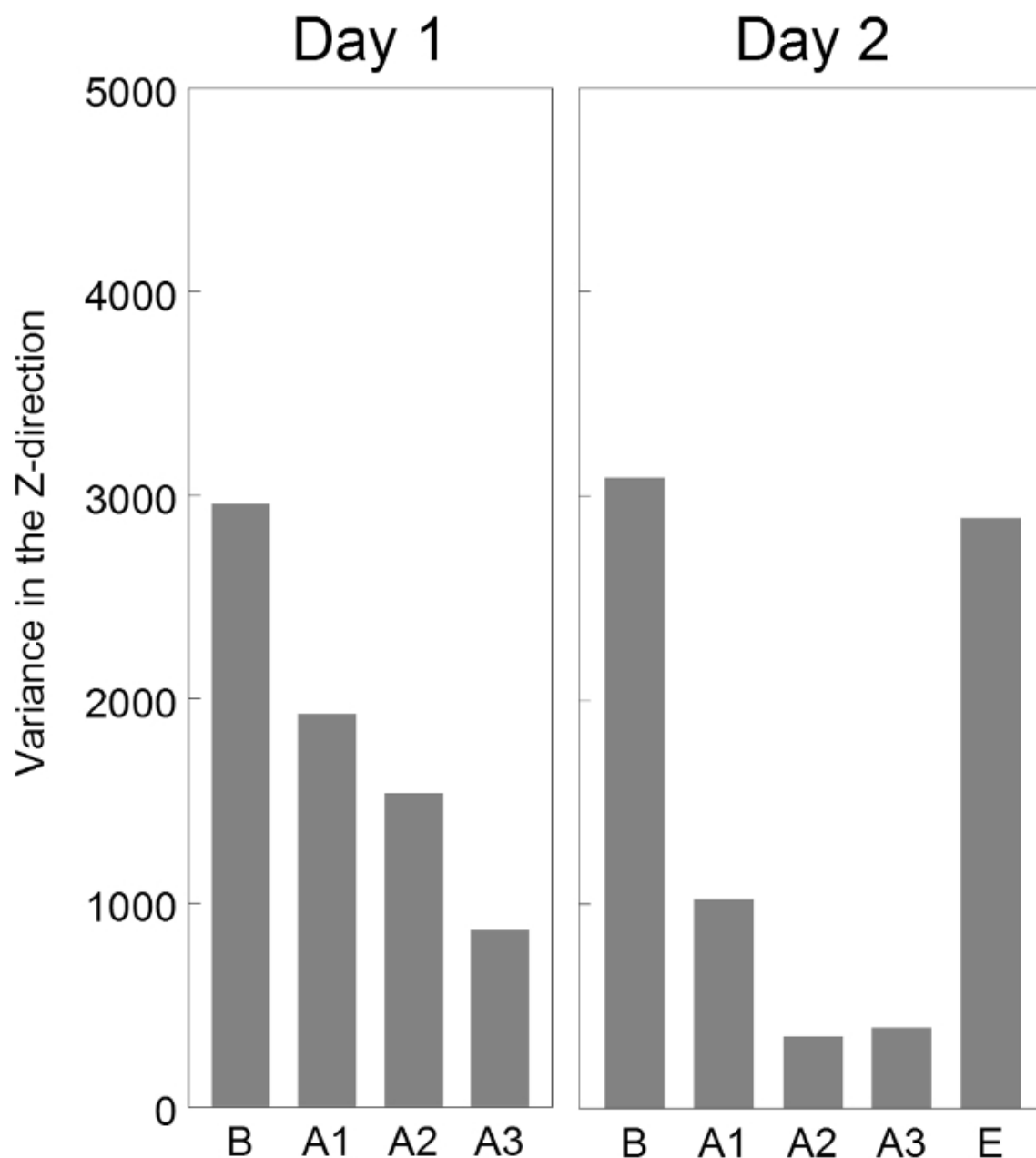


Figure 5: Example of a Learner with a high threshold (14 cm above table; 68% of leg length). This infant learned to move his feet around the threshold during the acquisition condition, thereby decreasing variance in the vertical z-direction. Note the increase in variance when the mobile no longer activates during the extinction condition. Raw data from Day 2 of this learner is presented in **Figure 2**. B = baseline, A = acquisition, E = extinction.

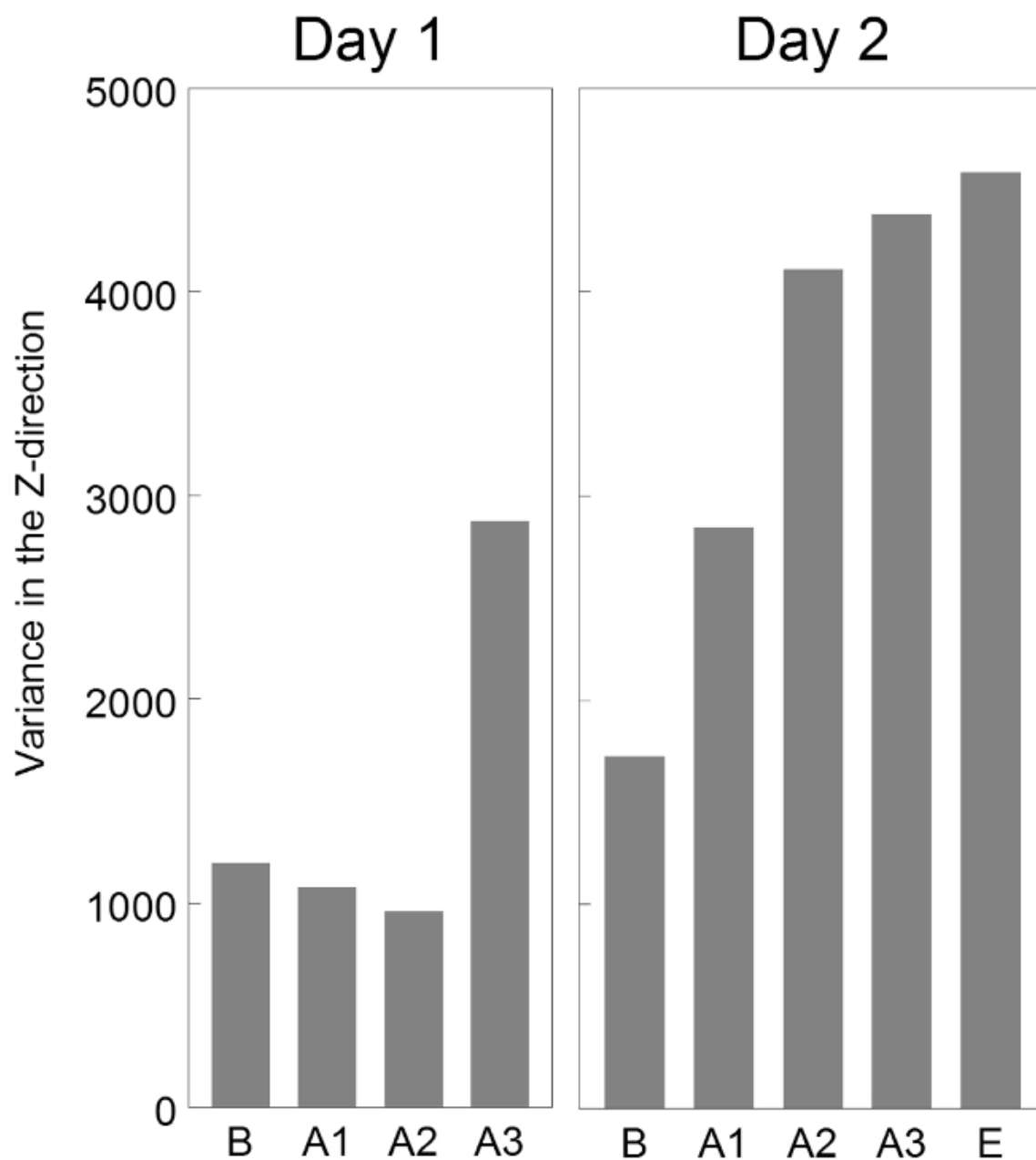


Figure 6: Example of a Learner with a low threshold (7 cm above table; 34% of leg length). This infant learned to lift his feet higher during the acquisition condition, thereby increasing variance in the vertical z-direction. B = baseline, A = acquisition, E = extinction.

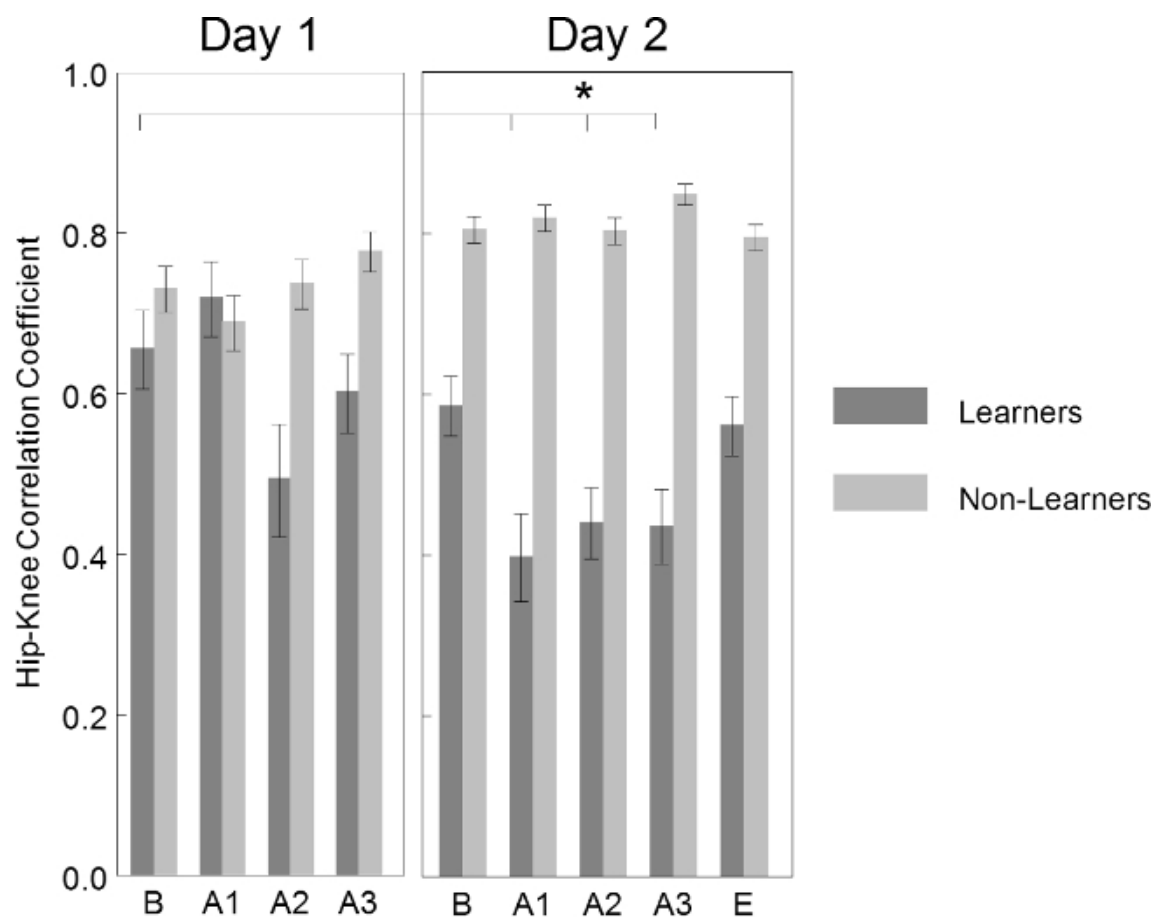


Figure 7: Learners versus Non-Learners: mean correlation coefficients of hip-knee pair by 2 min intervals. Infants were separated into Learners ($n = 8$) and Non-learners ($n = 12$) based on an individual learning criteria. Learners significantly decreased hip-knee angle correlation coefficient between the Day 2 acquisition condition and the Day 1 baseline condition (adjusted $p < 0.001$). B = baseline, A = acquisition, E = extinction.

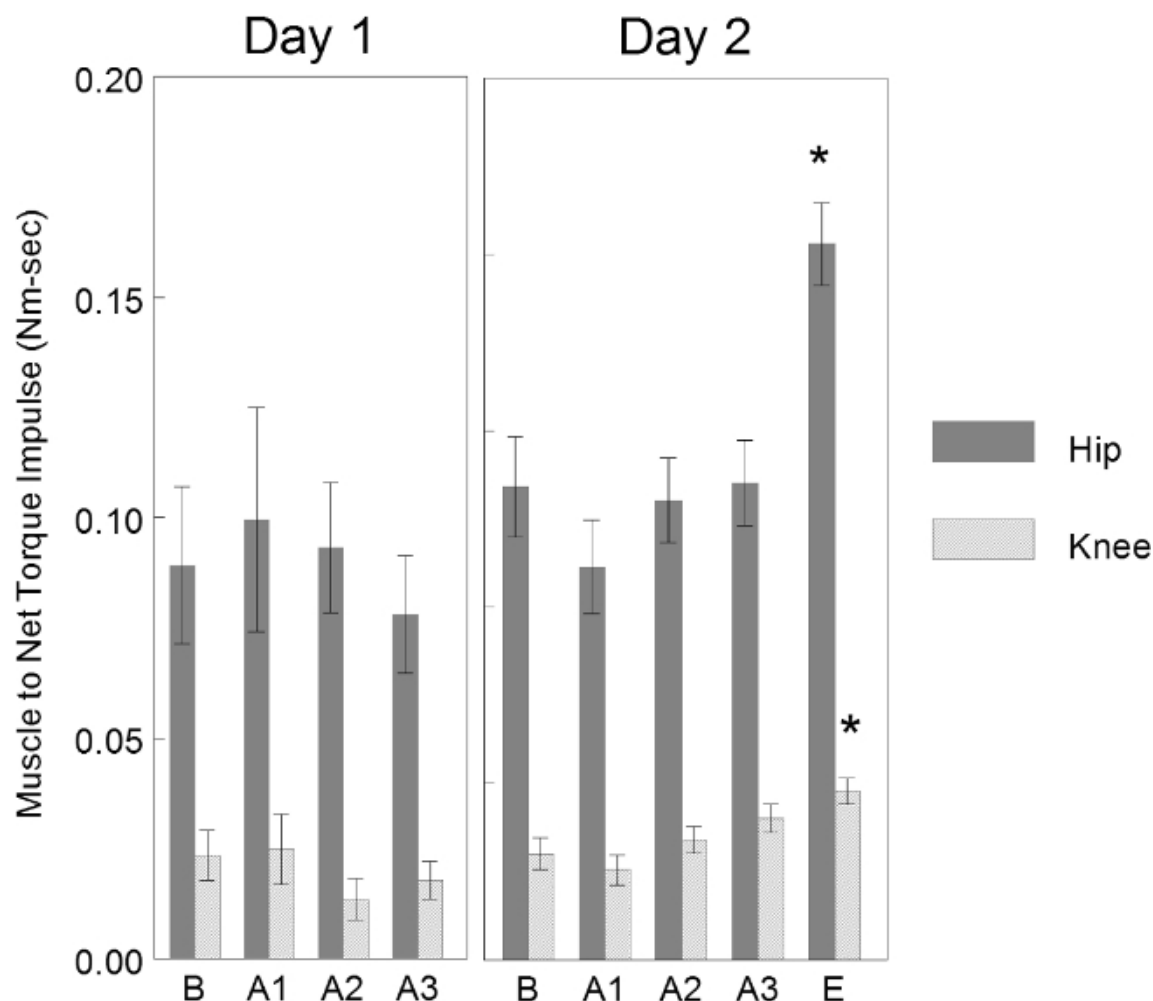


Figure 8: Learners: mean muscle to net torque impulse of the hip and knee by 2 min intervals. Learners ($n = 8$) significantly increased hip muscle torque impulse contribution to hip net torque impulse between the Day 2 extinction condition and all other conditions (adjusted $p < 0.001$). Learners also significantly increased knee muscle torque impulse contribution to knee net torque impulse between the Day 2 extinction condition and all other conditions except Day 1 baseline (adjusted $p < 0.001$). B = baseline, A = acquisition, E = extinction.

	Kick	Peak velocity	Hip joint Reversal	Peak velocity	Kick
	Initiation	1 st half of kick		2 nd half of kick	End
	M (SE)	M (SE)	M (SE)	M (SE)	M (SE)
Day 1 Baseline Learners	64.4 (6.7)*	57.1 (6.8)*	57.1 (7.5)*	57.7 (7.6)*	62.5 (6.0)*
Non-learners	60.3 (5.4)	52.6 (5.5)	53.2 (6.1)	51.8 (6.1)	58.3 (4.8)
Day 1 Acquisition Learners	64.1 (6.4)*	58.7 (6.6)*	58.3 (7.3)*	58.4 (7.4)*	66.3 (5.6)*
Non-learners	60.0 (5.2)	55.6 (5.4)	52.7 (5.9)	52.7 (6.0)	61.0 (4.6)
Day 2 Baseline Learners	65.9 (6.6)	63.6 (6.7)	62.7 (7.4)	61.9 (7.5)	66.7 (5.8)
Non-learners	44.7 (5.4)	42.6 (5.5)	39.3 (6.1)	37.8 (6.1)	48.6 (4.8)
Day 2 Acquisition Learners	76.3 (6.4)**	70.5 (6.6)**	70.5 (7.3)**	70.3 (7.3)**	73.2 (5.6)**
Non-learners	47.6 (5.2)	42.3 (5.4)	38.7 (5.9)	36.6 (6.0)	47.5 (4.6)
Day 2 Extinction Learners	65.6 (6.6)	60.5 (6.7)	61.7 (7.4)	61.7 (7.5)	66.7 (5.8)
Non-learners	48.1 (5.3)	46.7 (5.5)	43.9 (6.0)	42.3 (6.1)	49.8 (4.7)

Table 1: Learners versus Non-learners: relative phase of hip-knee pair by condition Infants were separated into Learners (n = 8) and Non-Learners (n = 12) based on an individual learning criteria. Within group, Learners significantly increased hip-knee angle relative phase at all 5 time points between the Day 2 acquisition condition and the Day 1 baseline condition (less in-phase coordination). Between groups, Learners, as compared to Non-learners, had significantly increased hip-knee angle relative phase (less in-phase coordination) at all 5 time points during the Day 2 acquisition condition. Note: SE = standard error. * = Significantly decreased from Learner Acquisition Day 2, $p < 0.001$ (more in-phase); ** = Significantly increased from Non-Learner Acquisition Day 2, $p < 0.001$ (less in-phase)

Discussion

Design of discovery-learning tasks for young infants

Discovery-learning tasks for young infants must be thoughtfully designed to assure that infants are independently discovering the contingency. In several mobile paradigms at the beginning of the acquisition condition, infants are either shown that the mobile activates by a non-contingent activation of the mobile^{7,22} or the leg of each infant is passively moved by the investigator to introduce the infant to the contingency⁹. In addition, caregivers and experimenters may provide additional reinforcement to support the infant's performance. Specific rules, as outlined here, are critical to assure that infants are independently discovering the contingency without outside influence.

It is also important that the dependent measure collected during a discovery-learning task is sensitive to changes in performance. The most critical aspect in this paradigm is the setting of the threshold for activation of the infant mobile. If the threshold is placed too high above the table, the infant may not activate the mobile frequently enough during acquisition to determine that it is his leg action that is activating the mobile. If the threshold is placed too low, the infant may have such a high level of %RLA at baseline that it is improbable that the infant will be able to increase %RLA sufficiently during acquisition to demonstrate performance or learning; for example, an infant with a baseline %RLA of 50% on Day 1 would need to activate the mobile for 75% of the 6 min acquisition condition of Day 2 to meet the individual learning criteria. Pilot testing confirmed that a standard threshold for each infant could not be used, rather the threshold must be computed individually for each infant from their baseline spontaneous leg action to assure that the baseline %RLA is approximately 20-30% of each infant's leg action.

Collection and analysis of position data from infant leg actions

This method uses position data collected from rigid bodies attached to joint segments, the standard method in adult biomechanical analysis. Previous research on infant leg actions have collected position data from individual LEDs affixed to joint centers^{13-15,23-28}. Collecting data from rigid bodies versus individual LEDs has several advantages. First, rigid bodies move less and fall off very infrequently as compared to individual LEDs. This allows for longer data collections (8-10 min) without interruptions to replace missing markers, which may distract infants from their discovery-learning task. Second, rigid bodies allow for a complete 3D kinematic and kinetic analysis of joint motion. Data collected with individual IREDs is analyzed and reported as though motion occurs only in the sagittal plane movements of flexion and extension. This leads to incomplete kinematic data. Data collected with individual IREDs also restricts kinetic analysis to a 2D kinetic approach, which likely yields inaccurate torque estimates during infant kicking actions which do not occur primarily in the sagittal plane. Although use of rigid bodies is a significant advancement in infant biomechanical research, infant rigid bodies are currently not available for purchase and require custom fabrication.

Limitations

One limitation of the method is that it is restricted to a laboratory setting due to the use of a motion capture system. Recruiting young infants to participate in laboratory-based research studies across multiple days is challenging.

This mobile paradigm reports lower percentages of infants who learned the task as compared to previous mobile paradigms. Due to several unique features of this paradigm, infants may require more than 2 days to demonstrate learning. First, infants are not shown that the mobile moves, rather they independently discover the contingency as their exploratory leg actions activate the mobile. Second, the paradigm requires more refined leg action than previous mobile paradigms and encourages a more mature, out-of-phase hip-knee coordination pattern that may be difficult for infants to learn to generate in two days³. Third, infants cannot demonstrate performance or learning by increasing leg actions when the mobile stops activating (*i.e.* during baseline or extinction⁵), rather infants need to remain engaged with the task and increase mobile reinforcement for the entire 6 min acquisition condition of Day 2 to demonstrate learning. Due to these unique features, it is hypothesized that an increase in the number of days participating in the task may result in more infants learning the task.

Future applications

This discovery-learning task can lead to new insights on how infants learn to modify their spontaneous movements to perform task-specific actions. By tracking the leg actions of infants while participating in a discovery-learning environment, it was demonstrated that infants change the position variance of their end effectors (feet), their hip-knee coordination patterns, and their hip and knee MUS torque impulse. This information can determine options infants have available to them when interacting with their environment and how they exploit these options to learn task-specific actions. It also provides a means to investigate not only how infants learn a task, but what they are learning. For example, Learners with a low threshold appeared to learn to kick higher, whereas Learners with a high threshold appeared to learn the location of the threshold.

Infants at risk for movement disorders provide a unique sample to investigate infant constraints that contribute to task-specific changes in action. The underlying pathology that places infants at risk contributes to differences in leg action due to impairments, such as decreased selective joint movement and decreased force-generating capacity of muscles. Tracking the leg actions of infants at risk for movement disorders during this or other discovery-learning tasks may provide an opportunity to quantify how specific impairments contribute to differences in task-specific leg action and also differences in how tasks are learned.

Once it is known how specific impairments of different populations of at risk infants influence early leg action, more principled research can be undertaken to determine how early leg action can be optimized for skilled function. Discovery-learning paradigms can be designed to support the leg action and learning of infants at risk for movement disorders. Specifically, environments can be constructed such that desired coordination patterns or force-production requirements are discovered by infants as they explore the relation between their leg action and its effects in the

constructed environment. These types of discovery-learning paradigms could not only support leg action, but could also support the learning abilities of young at-risk infants.

In summary, a method is described in which 3-4 month old infants learn a task by discovery and their leg movements are captured to quantify the learning process. Tracking the movements of infants while participating in discovery-learning tasks may provide an opportunity to quantify the learning process as infants explore the relation between their action and its effects on the world.

Disclosures

No conflicts of interest declared.

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References

- Gibson, E. J., Pick, A. D. *An Ecological Approach to Perception, Learning and Development*. Oxford University Press New York, NY (2000).
- Thelen, E., Smith, L. B. *A Dynamic Systems Approach to the Development of Cognition and Action*. MIT Press Cambridge, MA (1994).
- Sargent, B., Schweighofer, N., Kubo, M., Fetters, L. Infant exploratory learning: influence on leg joint coordination. *PLoS One*. **9**, (3), e91500 (2014).
- Rovee-Collier, C. K., Gekoski, M. J. The economics of infancy: A review of conjugate reinforcement. *Adv Child Dev Behav*. Reese, H. W., Lipsitt, L. P. **13**, 195-255 Academic (1979).
- Heathcock, J. C., Bhat, A. N., Lobo, M. A., Galloway, J. C. The performance of infants born preterm and full-term in the mobile paradigm: learning and memory. *Phys. Ther.* **84**, (9), 808-821 (2004).
- Haley, D. W., Weinberg, J., Grunau, R. E. Cortisol, contingency learning, and memory in preterm and full-term infants. *Psychoneuroendocrinology*. **31**, (1), 108-117 (2006).
- Angulo-Kinzler, R., Ulrich, B. D., Thelen, E. Three-month-old infants can select specific leg motor solutions. *Motor Control*. **6**, (1), 52-68 (2002).
- Tiernan, C. W., Angulo-Barroso, R. M. Constrained motor-perceptual task in infancy: effects of sensory modality. *J. Mot. Behav.* **40**, (2), 133-142 (2008).
- Chen, Y., Fetters, L., Holt, K., Saltzman, E. Making the mobile move: constraining task and environment. *Infant Behav. Dev.* **25**, (2), 195-220 (2002).
- Ohr, P. S., Fagen, J. W. Conditioning and long-term memory in three-month-old infants with Down syndrome. *Am. J. Ment. Retard.* **96**, (2), 151-162 (1991).
- Thelen, E., Hidden Ulrich, B. D. skills: A dynamical system analysis of treadmill stepping in the first year. *Monogr Soc Res Child Dev.* **56**, (1), 1-98 (1991).
- Soderkvist, I., Wedin, P. Determining the movements of the skeleton using well-configured markers. *J. Biomech.* **26**, (12), 1473-1477 (1993).
- Schneider, K., Zernicke, R. F., Ulrich, B. D., Jensen, J. L., Thelen, E. Understanding movement control in infants through the analysis of limb intersegmental dynamics. *J. Mot. Behav.* **22**, (4), 493-520 (1990).
- Jensen, J. L., Schneider, K., Ulrich, B. D., Zernicke, R. F., Thelen, E. Adaptive dynamics of the leg movement patterns of human infants: I. the effects of posture on spontaneous kicking. *J. Mot. Behav.* **26**, (4), 303-312 (1994).
- Fetters, L., Sapir, I., Chen, Y. P., Kubo, M., Tronick, E. Spontaneous kicking in full-term and preterm infants with and without white matter disorder. *Dev. Psychobiol.* **52**, (6), 524-536 (2010).
- Emmerick, R., Wagenaar, R. Effects of walking velocity on relative phase dynamics in the trunk in human walking. *J. Biomech.* **29**, (9), 1175-1184 (1996).
- Kelso, J. A., Scholz, J. P., Schoner, G. Nonequilibrium phase transitions in coordinated biological motion: critical fluctuations. *Physics Letters A*. **134**, (6), 8-12 (1986).
- Schneider, K., Zernicke, R. F. Mass, center of mass, and moment of inertia estimates for infant limb segments. *J. Biomech.* **25**, (2), 145-148 (1992).
- Sun, H., Jensen, R. Body segment growth during infancy. *J. Biomech.* **27**, (3), 265-275 (1994).
- Murray, R. M., Li, Z., Sastry, S. S. *A Mathematical Introduction to Robotic Manipulation*. CRC Press Boca Raton, FL (1994).
- Galloway, J. C., Koshland, G. F. General coordination of shoulder, elbow and wrist dynamics during multijoint arm movements. *Exp. Brain Res.* **142**, (2), 163-180 (2002).
- Angulo-Kinzler, R. Exploration and selection of intralimb coordination patterns in 3-month old infants. *J. Mot. Behav.* **33**, 363-376 (2001).
- Fetters, L., Chen, Y. P., Jonsdottir, J., Tronick, E. Z. Kicking coordination captures differences between full-term and premature infants with white matter disorder. *Hum. Mov. Sci.* **22**, 729-748 (2004).
- Jeng, S., Chen, L., Yau, K. Kinematic analysis of kicking movements in preterm infants with very low birth weight and full-term infants. *Phys. Ther.* **82**, 148-159 (2002).
- Jensen, J. L., Thelen, E., Ulrich, B. D., Schneider, K., Zernicke, R. F. Adaptive dynamics of the leg movement patterns of human infants: III. age-related differences in limb control. *J. Mot. Behav.* **27**, 366-374 (1995).
- Piek, J. P. A quantitative analysis of spontaneous kicking in two-month-old infants. *Hum. Mov. Sci.* **15**, 707-726 (1996).
- Thelen, E. Developmental origins of motor coordination: Leg movements in human infants. *Dev. Psychobiol.* **18**, 1-22 (1985).
- Vaal, J., van Soest, A. J., Hopkins, B., Sie, L. T. L., van der Knaap, M. S. Development of spontaneous leg movements in infants with and without periventricular leukomalacia. *Exp. Brain Res.* **135**, 94-105 (2000).