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Change in Action: How Infants Learn to Walk Down Slopes

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Abstract

A critical aspect of perception-action coupling is the ability to modify ongoing actions in accordance with variations in the environment. Infants' ability to modify their gait patterns to walk down shallow and steep slopes was examined at three nested time scales. Across sessions, a microgenetic training design showed rapid improvements after the first session in infants receiving concentrated practice walking down slopes and in infants in a control group who were tested only at the beginning and end of the study. Within sessions, analyses across easy and challenging slope angles showed that infants used a "braking strategy" to curb increases in walking speed across increasingly steeper slopes. Within trials, comparisons of infants' gait modifications before and after stepping over the brink of the slopes showed that the braking strategy was planned prospectively. Findings illustrate how observing change in action provides important insights into the process of skill acquisition.

Observing Change in Action

Most studies with infants and children focus on the outcome of learning and development rather than on the processes of change. The literature is filled with descriptions of children's deficits at one age and accomplishments at a later age, as if learning has only disjointed endpoints like before and after snapshots rather than a trajectory that takes shape over multiple observations (Siegler & Munakata, 1993). Typically, performance at various levels of difficulty is analyzed in terms of group means at each level, as if patterns of differential performance across levels are identical across children rather than composed of individual functions for each child. Each trial is summarized in terms of one data point, ignoring the behavioral sequence that led up to that outcome.

The tide is shifting. Recent enthusiasm for microgenetic methods, individual functions, and within-trial analyses in developmental psychology has led to new interest in describing learning trajectories and a stronger focus on understanding processes of change (Adolph & Robinson, in press; Alibali & Goldin-Meadow, 1993; Dixon, 2005; Siegler, 2006). With a microgenetic design, pre- and post-test results are supplemented by data from the intervening sessions so as to reveal the shape of the underlying trajectory. By modeling individual functions, researchers retain the details of each child's course of learning within a session. And a within-trial approach focuses on the unfolding of behavior in real time as children cope with the problem.

Historically, studies of infant motor development have proven to be an important exception to outcome-oriented research (e.g. Adolph, 1997; Breniere & Bril, 1998; Corbetta & Bojczyk, 2002; McGraw, 1935; Shirley, 1931; Thelen & Ulrich, 1991; Vereijken & Thelen, 1997). One reason for the long tradition of detailed descriptions of change in infant motor skill acquisition is that change in motor action is readily observable (Adolph & Berger, 2006). Changes in the quantity and quality of infants' movements can be described over multiple, nested time scales —from the sequence of behaviors within a trial to performance across trials and sessions, from the milliseconds of each walking step to the improvements in walking patterns over the toddler period.

Previous work with infants descending slopes illustrates the nested processes involved in learning to select motor actions in accordance with variations in the environment (Adolph, 2002, 2005). Weekly microgenetic analyses show that infants slowly learn to distinguish slopes that are safe for walking from slopes that are impossibly risky (Adolph, 1997; Adolph, Tamis-LeMonda, Ishak, Karasik, & Lobo, in press). In their first weeks of walking, infants march straight over the edge of impossibly steep slopes, requiring rescue by an experimenter. Over weeks of everyday walking experience, responses become increasingly adaptive; attempts to walk gradually gear in to the limits of infants' walking skill, regardless of whether infants have repeated practice on slopes or not (Adolph, 1997). Experienced walking infants select actions adaptively based on the degree of slope relative to their current abilities: They walk down safe slopes within their abilities and slide down or avoid steeper slopes beyond their abilities (Adolph, 1995; Tamis-LeMonda et al., in press). At a finer grain of analysis within sessions, individual response functions are graded across degrees of slope and scaled to each infant's current level of walking skill (Adolph, 1995, 1997; Adolph & Avolio, 2000). At an even finer grain of analysis within trials, experienced walkers distinguish the different possibilities for action by generating perceptual information through spontaneous exploratory activity as they approach the brink of the slope (Adolph, Eppler, & Gibson, 1993; Adolph, Eppler, Marin, Weise, & Clearfield, 2000; Eppler, Adolph, & Weiner, 1996). They slow down, stop at the top of the slope, peer over the edge, and touch the sloping surface with their feet.

This process of learning to select the appropriate action (i.e., deciding whether to walk, slide, or avoid in accordance with the degree of slope) is only one aspect of adapting motor actions to variations in local conditions. A second, equally important, but neglected aspect of perception-action coupling involves continuous control of ongoing activity, that is, modifying and fine-tuning the selected motor actions (Fajen, 2007; Stoffregen, 2000; Whiting, 1984). Despite ample evidence that adults (e.g. Joh, Adolph, Narayanan, & Dietz, 2007; Regia-Corte & Wagman, in press) and experienced walking infants can select actions adaptively for descending slopes, researchers know little about walkers' ability to modify ongoing gait patterns to cope with variations in slope (or other changes in the environment). The lack of research in this area is surprising because continuous gait modifications are more common in everyday locomotion, at least in older children and adults. Most changes in the everyday environment are not extreme enough to warrant an alternative method of locomotion. While navigating around obstacles, coping with variations in friction and rigidity, and going up and down stairs and slopes, older children and adults rarely switch from walking to sliding or climbing on all fours. Instead, we keep on walking but modify our gait patterns by changing the position of our bodies, altering our walking speed and step length, lifting our feet higher, or planting our feet more firmly on the ground. Moreover, the question of gait modifications is important for understanding motor skill acquisition because variations in local conditions necessitate continual adjustments in ongoing actions. As in deciding whether to walk, deciding how to walk requires prospective control. Gait modifications are most effective when they are planned ahead of time rather than executed reactively in the midst of a fall.

Walking Down Slopes

Sloping ground provides a rich test case for assessing ongoing gait modifications. When infants walk down a slope, gravity pulls the body forward in addition to downward. The steeper the slope, the larger the forward force and subsequent increases in walking speed. Without gait modifications, infants pick up speed from step to step and end up running with their torso in front of their feet (Adolph, 1997; McGraw, 1935). Furthermore, impact forces at foot contact increase with steeper downhill slopes and faster walking speeds, requiring larger counteracting muscle forces and increased eccentric muscle actions to control gait and maintain balance. Loss of control could lead to a fall with serious consequences, especially when falling forward with the trunk leading the feet.

Alternatively, infants could use a “braking strategy” to curb the build up of walking speed and impact forces and to minimize the consequences of falling. Presumably, falling would be less serious if infants are moving more slowly. Moreover, if they lean backward rather than forward, they would be more likely to fall on their bums rather than face forward. Braking can be achieved by decreasing step length and/or increasing step time. Large adjustments in both factors would lead to a reduction in walking speed and impact forces on slopes compared with flat ground. In adults, the braking strategy is implemented primarily by decreasing step length (Leroux, Fung, & Barbeau, 2002; Redfern & DiPasquale, 1997). Adults shorten step length by increasing the flexion of the supporting knee while lowering the body onto the moving foot (Redfern & DiPasquale, 1997). They further counteract the gravitational forces that pull the body forward by tilting the trunk and pelvis backward to shift the center of mass backward (Leroux et al., 2002). Step time is simultaneously decreased enough to maintain the same walking speed displayed on flat ground, but not so much as to allow a build up of walking speed with steeper slopes (Leroux et al., 2002; Redfern & DiPasquale, 1997). Previous work suggests that infants are capable of implementing a braking strategy but only after many weeks of walking experience. At 14 months of age, modifications in step length and walk time are only loosely related to slope angle and infants frequently cope by running down slopes (Adolph & Avolio, 2000). Anecdotally, we have observed older, more experienced walking infants use the braking strategy to descend tremendously steep (36° – 44°) slopes, a performance so nerve-wracking that caregivers and experimenters held their breath as the infants took step after tiny step until arriving at the landing platform. Similarly, McGraw (1935) described one child’s descent of an 18° slope as a progression of “tiny steps, so tiny indeed that he scarcely lifted the foot off the slide as he moved it forward” (p. 150).

Current Study

The current study expands on previous work that described how infants decide whether to walk down slopes, by examining infants’ decisions about how to walk. We studied gait modifications at various nested time scales to describe change in motor action across sessions, slope angles, and from step to step. Across sessions, we used a microgenetic training design to examine changes in gait modifications as a function of experience and type of practice. Within each session, we used correlation and slope coefficients (r and b) to summarize the relationship between slope angle and behavioral measures in terms of individual response functions across levels of difficulty. And within trials, we compared infants’ behaviors as they approached the slope and after stepping over the brink to address the question of prospective control in their use of the braking strategy.

The study had three aims. Our first aim was to document infants’ use of the braking strategy. Do infants succumb to gravity, building up speed on increasingly steeper slopes? Or do they brake by adjusting step length, step time, or both? A related and critical question in terms of perception-action coupling was how precisely gait modifications are attuned to slope angle. Based on McGraw’s rich descriptions and our own anecdotal and experimental data, we expected that infants could eventually implement a braking strategy. Although adults maintain walking speed relative to flat ground by decreasing both step length and step time with increase in slope angle, findings from Adolph and Avolio (2000) suggested that infants might reduce walking speed relative to flat ground by decreasing step length and increasing step time on increasingly steeper slopes. However, in previous work with adults (e.g. Leroux et al., 2002; Redfern & DiPasquale, 1997), gait patterns were observed at only at few degrees of slope and these were often limited to relatively shallow slopes. In previous studies with infants (e.g. Adolph & Avolio, 2000), comparisons included impossibly steep slopes that precluded walking and necessitated alternative sliding positions or avoidance.

In the current study, all of the slopes were walkable, but slope angles ranged from easy to challenging in 2° increments over a target range spanning 18°. To ensure comparable levels of difficulty across infants with varying levels of walking skill, we used a psychophysical procedure to normalize the range of slope angles to each infant's level of walking skill. We summarized each infant's performance at each session in terms of correlation and slope coefficients. The correlation coefficient, *r*, characterized how consistently infants modified their gait at each increasing slope angle; the slope coefficient, *b*, characterized the amount of change relative to the increase in slope angle. To avoid the practical difficulties of instrumenting the infants with markers or recording devices, we relied primarily on video analyses of infants' gait modifications. We indexed an approximation of average step length by counting the number of steps to walk down each slope (the larger the step number, the smaller the average step length) and step time by the overall time to walk that same distance (the longer the walk time, the longer the average step time). In addition, we collected footfall measures in a final footprint session so that we could assess step length directly at each location along the slope.

Our second aim was to determine whether infants decide to modify their gait prospectively while approaching the brink of the slope or reactively while attempting to walk down. Optimally, infants should implement a braking strategy prospectively. To adjust step length and/or step time before stepping over the brink, they would need to relate perceptual information for slope angle with the consequences for curbing walking speed and maintaining balance on the slope. Although infants also obtain perceptual feedback after stepping onto the slope, if their feet hit the slope while their bodies are moving too quickly, they might not have the strength and control to implement the braking strategy mid-slope. Previous experiments show that experienced walking infants select locomotor actions prospectively for descending slopes (for review, see Adolph, 2002; Adolph, 2005; Adolph & Berger, 2006). They switch from walking to sliding positions before stepping over the brink. In addition, latency and exploratory touching from the starting platform increase on steeper slopes suggesting that infants are prompted to generate additional perceptual information as they recognize the increasing risk. Thus, in the current study, we asked whether the decision to modify gait is also prospective. Within trials, we compared infants' behaviors on the starting platform with their behaviors on the slope. As in previous work, we coded latency and exploratory touching from video recordings, but here the focus was on safe slopes that infants walked down successfully. Would infants also increase exploratory activity on slopes that they decided to walk down? In addition, we observed infants' gait modifications as they approached the brink by counting the number of walking steps from video and from footfall measures in the final session.

The third aim was to examine the role of practice in infants' gait modifications. Because previous work indicated rudimentary use of a braking strategy in 14-month-olds (Adolph & Avolio, 2000), we began testing infants at 15 months, on the assumption that an additional month of everyday walking experience might enhance our chances of observing more consistent and finely tuned use of the braking strategy. Infants in two experimental groups received three weeks of intense practice walking down slopes. In accordance with the literature on motor learning in adults and children (e.g. Green, Whitehead, & Sugden, 1995; J. Shea & Morgan, 1979; Wulf, 1991), we tested infants over varied levels of difficulty. In contrast to typical motor learning studies, we did not compare the two extreme schedules of variable practice, blocked versus random, but ordered versus random presentation of trials. Infants in an ordered trial group received slopes in gradually increasing and decreasing orders (a special case of a serial practice schedule, cf. C. H. Shea, Lai, Wright, Immink, & Black, 2001), and infants in a random trial group received slopes in random orders. With the ordered trial presentation, the slope that infants had just walked down was very similar to the one they were currently facing. Thus, if adjustment of step length and step time was successful on one trial, infants might be more likely to use the same gait modifications on the next slope, thereby facilitating discovery and fine-tuning of the braking strategy. With a random trial presentation, the just-prior slope was likely to be different from the current one. Thus, infants would be required to assess their ability to walk down each slope anew. As in a variable practice regimen (Gentile, 2000), infants might take longer to discover a braking strategy, but show more consistent and pronounced learning (evidenced by larger correlation and slope coefficients) at the end of the training period when all infants were tested with random presentation orders. Infants in a control group were tested only at the beginning and end of the study with random presentation orders. Presumably, if additional practice walking down slopes were beneficial, infants in the training groups would outperform infants in the control group.

In a typical training study, learning would be assessed by the amount of change from pre- to post-test sessions between experimental and control groups. Accordingly, in the current study, we summarized overall changes from pre- to post-test sessions across the three practice groups. However, we also observed the process of change over the 8 practice sessions, the dozens of trials within each session, and from step to step over the course of a trial. Analyses of changes across practice sessions reveal whether the rate of learning differed for ordered and random practice regimens. Analyses of changes across trials reveal whether infants modified their step length and step time in accordance with the slope angle. Finally, analyses of changes within trials reveal whether infants decide to implement a braking strategy prospectively before walking over the brink or reactively part way down the slope.

Method

Participants

Infants were recruited from newspaper advertisements and mailings to a diaper service. As souvenirs of their participation, families received a set of small gifts. Twenty-five infants completed the study. Most were White and from middle-class families. On average, infants were 15.42 months old (*SD* = 0.53) at their first session and 16.18 months old at their tenth session (*SD* = 0.56). We required infants to walk down slopes ≥14° at their first test session as a criterion for participation to ensure that they could be tested over a sufficient range of shallow and steep increments. Thus, all infants were relatively skilled walkers. Parents reported their infants' locomotor histories in the context of a structured interview using calendars and baby books to augment their memories (Adolph, Vereijken, & Shrout, 2003). On average, infants had 3.74 months of walking experience (*SD* = 1.55) at their first session.

Initially, infants were randomly assigned to a practice group (7 boys, 6 girls) or a control group (6 boys, 6 girls). To assess whether type of practice affects learning, infants in the practice group were then further assigned to an ordered (3 boys, 3 girls) or random practice regimen (4 boys, 3 girls). Due to frequent testing for the practice groups, we could only manage data collections for a few infants in the practice groups at one time, so it was possible to run twice as many infants in the control group during the same time period. There were no differences between the three groups in age or walking experience at sessions 1 or 10. Three additional infants (2 girls, 1 boy) did not complete the experiment. One girl became fussy at her first test session and her parents declined to participate, one girl missed scheduled practice sessions, and one boy could not walk down a 14° slope. Infants wore only rubber-soled shoes, diapers, and an undershirt while walking down slopes.

Sloping Walkway

We tested infants on an adjustable sloping walkway (Figure 1). Flat starting and landing platforms flanked an adjustable sloping section (each 86 cm wide × 91 cm long). The middle sloping section adjusted from 0° to 90° in 1°-increments via a push-button remote that operated the drive-screw of a garage door opener. Each segment of the apparatus was large enough to

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accommodate several walking steps. Safety nets stretched along the sides of the walkway from wooden posts at each corner. The entire walkway was covered with plush carpet to provide traction and cushioning. A protractor attached to the side of the walkway displayed the slope angle.

Procedure

We used a microgenetic training design to track changes across sessions in infants' ability to modify their walking patterns on slopes. Infants in the two practice groups were observed two to three times per week for a total of 10 slope sessions. Session 1 was a pre-test to determine the extent to which infants spontaneously used a braking strategy prior to practice on slopes. Session 10 was a post-test to document infants' use of a braking strategy after three weeks of practice. Sessions 2–9 were practice sessions in which infants had an opportunity to discover and hone their use of a braking strategy by repeatedly walking down slopes. In addition, 12 of the 13 infants in the practice groups were observed in a final "footprint" session in which we collected footfall measures of their gait modifications on shallow and steep slopes. The remaining infant was too fussy and did not contribute footprint data. We only obtained footprint data from infants in the two practice groups because their families were already comfortable with the intense data collection schedule. Infants in the control group were observed only twice, at sessions 1 and 10.

Pre-and post-test sessions lasted 120 minutes and practice and footprint sessions lasted 60 minutes. Each trial lasted 60 s or until infants began to descend, whichever occurred first. To assess learning within trials, we observed infants on the starting platform as they approached the slope and on the slanted section of the walkway as they navigated descent. Trials began with infants in a standing position in the middle of the starting platform. Parents stood at the end of the landing platform and encouraged infants to walk down. An experimenter followed alongside infants to ensure their safety (illustrated in Figure 1). An assistant panned a camera from the side of the walkway to record infants' exploratory behaviors on the starting platform and walking patterns on the slope. A second camera recorded the slope angle indicated by the protractor. Both camera views were mixed on-line onto a single video frame.

Walking thresholds. A braking strategy is most useful for navigating challenging slopes at the upper limits of infants' walking skill. However, walking ability varies widely among infants. An easy slope for some infants can be unmanageably difficult for others. Thus, to ensure a comparable range of easy and challenging slopes across infants, we normalized the range of test slope angles to each infant's ability to walk down slopes.

Pre- and post-test sessions 1 and 10 began with a psychophysical procedure to derive individualized estimates of walking skill (described in Adolph, 1995, 1997). We estimated the steepest slope infants could walk down without falling—a "walking threshold." The experimenter coded each trial on-line as a successful walk (from starting to landing platforms), a failure (attempted to walk, but fell), or a refusal to walk (slid down or avoided descent). For the purpose of estimating walking thresholds, we treated failures and refusals as equivalent unsuccessful outcomes. Protocols began with an easy 4° baseline slope. The experimenter increased the slope angle by 6° after each successful trial until infants responded unsuccessfully on two consecutive trials. Then, the experimenter presented the 4° baseline slope to renew infants' motivation to walk. Re-entering the protocol after the last unsuccessful trial, the experimenter decreased the slope angle by 4°. The procedure continued until the experimenter narrowed in on the walking threshold—the steepest slope infants walked down successfully on ≥ 2/3 trials and fell or refused on ɥ 2/3 trials at each of the next three 2° increments. The protocol required M = 26.18 trials (SD = 8.18) to estimate the threshold.

Test trials. Next, to assess change across trials and various degrees of slope, the experimenter tested infants on a target range of slopes. We reasoned that infants would not need a braking strategy on easy slopes far shallower than their threshold and could not walk down impossible slopes far steeper than their threshold, but that challenging slopes slightly shallower and steeper than the threshold would warrant use of a braking strategy. Since walking thresholds varied because of individual differences in walking ability, the target range was normalized around each infant's walking threshold. The target range consisted of 10 slopes varying in 2° increments: 7 slopes shallower than the walking threshold (represented by −14° to −2°), the walking threshold (represented by 0°), and 2 slopes steeper than the walking threshold (represented by +2° and +4°). At test sessions 1 and 10, infants received 2 blocks of test trials at each of the 10 slopes in the target range for a total of 20 test trials. Trial presentation was randomized within blocks. A new target range was defined at session 10, normalized around infants' new walking threshold.

During practice sessions 2–9, infants in the ordered and random trial groups received 3 blocks of test trials at each of the 10 slopes in their target range for a total of 30 trials. Infants in the ordered trial group received slopes in gradually increasing and decreasing 2°-increments (e.g., …18°, 20°, 22°, 24°…). Infants in the random trial group received slopes in random orders (e.g., …14°, 6°, 24°, 10°…); thus, their practice regimen was similar to the random trial presentation in sessions 1 and 10. Across practice sessions, infants in the ordered trial group received increasing trials and decreasing trials first at alternating sessions. Infants in the random trial group received different random trial orders at each session, with each random order constant over the three repetitions. We expected that infants might sometimes fall or refuse to walk down the most difficult slopes, at the threshold increment and steeper, but that these challenging slopes might become more manageable over the 8 practice sessions. Trials where infants fell or refused to walk were not repeated. Thus, infants sometimes contributed fewer than 30 test trials with successful walks.

Footfall measures. In a final footprint session, we used a footprint method (Adolph et al., 2003) to capture modifications in step length during the approach to the slope and as infants walked down the sloping ramp onto the landing platform. This footprint session was scheduled within 2 days of session 10 for infants in the two practice groups. The experimenter replaced the carpet on the walkway with a long strip of butcher paper. An assistant placed moleskin tabs on the toes and heels of infants' shoes and dabbed them with colored ink. As infants walked over the paper, their footfalls created a trail of inked footprints. As in the earlier slope sessions, the experimenter walked beside infants to ensure their safety while caregivers encouraged infants to walk to the end of the landing platform. Pilot testing showed that infants would slip on the butcher paper if we tested them at their walking threshold. Thus, infants received 2 trials on relatively shallow slopes at 20% of their session 10 walking threshold and 2 trials on relatively steep slopes at 80% of their session 10 walking threshold. If the computed value of the target shallow and steep slopes was not a whole number, we rounded to the next integer. For example, if the walking threshold was 28°, the shallow slope (5.6°) was rounded to 6°, and the steep slope (22.4°) was rounded to 22°.

Data Coding

Data were coded from videotape using a computerized video coding system, MacSHAPA (http://www.openshapa.org/). First, a primary coder scored all trials for all sessions as successes, failures, and refusals. For sessions 1 and 10, she recalculated walking thresholds based on the video data. Video-based thresholds were in 100% agreement with the thresholds calculated on-line. Next, for each successful trial at sessions 1 and 10, the primary coder scored three measures of prospective planning in the first part of the trial before infants stepped onto the slope: Step number on the starting platform reflected gait modifications as infants approached the brink; foot touches reflected haptic exploration of the slope angle and friction; and latency reflected hesitation prior to descent as well as the time required for gait modifications and touching. For step number, she counted from the first step after the experimenter placed infants in a standing position on the starting platform until the last step before they stepped onto the slope (including steps in place, back steps, and pivoting steps). Touches were scored categorically— as "no" if infants did not make physical contact with slopes prior to walking down and "yes" if infants probed slopes by poking out a foot, sliding a foot over the slanting surface, or rocking back and forth at the brink. Latency was the duration from the first video frame when the experimenter released infants on the starting platform until the first step onto the slope and thus included time spent in gait modifications and touching. The primary coder also scored two measures of gait modifications in the second part of each trial after infants stepped onto the slope: Step number from the top to bottom of the slope and the duration of time for infants to walk that distance. Analogous to the criteria for scoring step number on the starting platform, the coder counted the number of steps from the first step onto the slope to the first step onto the landing platform. Walk time was the duration from the first video frame of foot contact at the top of the slope to foot contact on the landing platform.

A second coder scored the same variables for 25% of the data for each child. Coders agreed on 92% of trials for success, failure, and refusal codes ($\kappa = .82$, $p < .02$) and 100% of trials for touching ($\kappa = 1.00$, $p < .001$). The correlation between coders' scores was high for step number on the starting platform ($r(738) = .99$) and slope ($r(1175) = .96$), latency ($r(960) = .97$), and walk time ($r(1170) = .95$); all p's < .001.

To score infants' footfall patterns, assistants overlaid a transparent grid on the butcher paper and obtained the x and y coordinates of infants' toe and heel prints relative to the beginning and end of the slope. Footprint measures were accurate within .25 cm.

Results

Across all 10 sessions, infants fell on 16.72% of trials and refused to walk on 12.19% of trials. Most of these failures and refusals occurred on steep slopes: Although only 35.74% of the 5431 trials in the dataset occurred on slopes 20° or steeper, 73.57% of infants' failures and 75.38% of their refusals occurred at those steep increments. Falls included trials where infants used a running strategy and were rescued by the experimenter as they fell spread-eagled in midair or collapsed on the landing platform and trials where infants tried to use a braking strategy but slipped backward or lost their balance. Refusals included trials where infants used a sliding position and trials where they avoided descent. The frequency of failures and refusals did not change over sessions. All trials (successes, failures, and refusals) were used to calculate walking thresholds at sessions 1 and 10. Because gait modifications were our primary focus, we included only successful walk trials in further analyses. At sessions 1 and 10, infants averaged 29.86 ($SD = 5.58$) successful walk trials because we included data from the psychophysical procedure and 20 test trials. At practice sessions 2 to 9, they averaged 21.31 ($SD = 4.94$) successful walk trials because they fell or refused to walk on some of the 30 test trials.

Walking Thresholds

Walking thresholds varied widely, underscoring the importance of characterizing easy and challenging slopes relative to each infant's walking ability. Across infants and sessions, thresholds ranged from 14° to 38°. As shown in Figure 2, walking thresholds increased from session 1 ($M = 21.68°$, $SD = 4.11$) to session 10 ($M = 27.52°$, $SD = 6.31$), and thresholds were positively correlated across sessions, $r(25) = .64$,$p < .001$. A 2 (sessions 1 and 10) × 3 (ordered, random, and control groups) repeated measures ANOVA on walking thresholds revealed only a main effect for session, $F(1, 22) = 40.62$, $p < .001$.

Use of the Braking Strategy on Slopes

Across sessions, infants produced a wide range of gait modifications while walking down slopes. Step number from top to bottom of the slope ranged from 3 to 26 (*M* = 7.99) and walk time ranged from 0.60 s to 18.40 s (*M* = 3.08 s). On trials with the smallest step numbers and shortest walk times, infants ran down the slopes. On trials with the largest step numbers and walk times, infants crept forward an inch at a time with long pauses between steps. Thus—at least on some trials—infants used a braking strategy, and they did so by increasing both step number and walk time: Across infants and sessions, step number and walk time increased in concert; the average correlation was $r = .84$ ($SD = 0.13$); in contrast to adults, none of the 154 correlations were negative to suggest that infants sometimes decreased walk time while increasing step number.

A critical issue for perception-action coupling was what prompted the gait modifications. We eliminated the possibility that falling on previous trials elicited more prudent gait modifications on subsequent trials. Step number and walk time were similar on trials following successes ($M = 8.20$, $SD = 1.79$ and $M = 3.45$ s, $SD = 1.40$, for step number and walk time, respectively) and failures ($M = 8.50$, $SD = 2.34$ and $M = 3.64$ s, $SD = 1.91$, for step number and walk time, respectively). Thus, we asked whether infants tailored their gait modifications to the challenges posed by increasingly steeper slopes. That is, did step number and walk time increase with larger slope angles so as to curb increases in walking speed? And if so, was systematic use of the braking strategy affected by practice walking down slopes? We addressed these questions by summarizing the data within sessions for individual infants and comparing these summary statistics across sessions to assess the effects of practice. For each infant's data at each session, we computed the best fitting regression line between slope angle and step number or walk time. We also computed curvilinear functions, but these did not improve the fit. The correlation coefficient, *r*, reflected the consistency of gait modifications with incremental changes in slope angle (i.e., spread of data points around the regression line); larger values of *r* indicate more consistent responding at each increasing slope angle. The unstandardized slope of the regression line, *b*, reflected the rate of change in responding across the range of slopes; larger values of *b* indicate more pronounced gait modifications on steeper slopes. Note that the same correlation coefficient could be accompanied by different slope coefficients, and different correlation coefficients could be produced by functions with the same slope coefficient. We examined effects of practice with comparisons between test sessions and practice groups. To compare the three groups at sessions 1 and 10, we used 2 (sessions 1 and 10) × 3 (ordered, random, and control groups) repeated measures ANOVAs on each regression coefficient. For variables that showed a session effect, we compared the random and ordered groups across practice sessions using 8 (sessions 2 through 9) × 2 (ordered and random groups) repeated measures ANOVAs.

Figure 3 illustrates gait modifications for one infant in the ordered practice group at each session for each slope. At session 1, when the infant's threshold was 24°, step number ranged from 5 to 21 and walk time from 1.13 s to 9.10 s. But use of the braking strategy was frequently haphazard. For instance, the trials with 5 and 21 steps were both produced at the same 18° slope. Correlation coefficients were relatively low (*r*'s = .22 and −.05, for step number and walk time, respectively) and slopes of the regression lines were relatively flat (*b*'s = .12 and -.01). Use of the braking strategy became more systematic in the eight practice sessions. Values of *r* and *b* rapidly increased at session 2, indicating more consistent and pronounced responding in accordance with the slope angle. At session 10, when his threshold increased to 30°, the infant still produced a wide range of gait modifications: Step number ranged from 5 to 22 and walk time ranged from 1.53 s to 11.47 s. However, now the braking strategy was applied more systematically. The trial with 5 steps, for example, was at the shallowest 4° slope and the trial with 22 steps was at the steepest 30° slope. Use of the braking strategy was beautifully attuned to gradual changes in the slope angle (r's = .90 and .52, for step number and walk time, respectively); the change in gait modifications was more pronounced with each increment (b's = .52 and .16).

Like the exemplar infant illustrated in Figure 3, most infants showed dramatic improvements across sessions. At session 1, 48% of the infants had correlation and slope coefficients that differed from 0 for step number and 36% for walk time. In contrast, at session 10, 96% of infants had correlation and slope coefficients that differed from 0 for step number and 72% for walk time. Initial one-way ANOVAs showed no differences between the three groups at session 1; therefore, in subsequent analyses, we examined whether group differences emerged over sessions.

As shown in Figures 4A–B, in all three groups, the average value of the correlation coefficient, r, was always positive and increased over sessions for both step number and walk time. However, overall values of r tended to be greater for step number (M = .50, SD = .17) than for walk time (M = .39, SD = .17); $t(24) = 7.87$, $p < .001$. ANOVAs comparing the three groups at sessions 1 and 10 revealed only a main effect for session for step number, $F(1,22) = 37.81$, $p < .001$ (M = .33, SD = .27, and M = .66, SD = .17, for session 1 and 10, respectively), and walk time, $F(1,22) = 15.80$, $p < .01$ (M = .27, SD = .26, and M = .51, SD = .22, for session 1 and 10, respectively). The ANOVA comparing the ordered and random groups across the 8 practice sessions for step number revealed only a main effect for group, $F(1,11) = 5.96$, $p < .05$ (M = .62, SD = .06, and M = .47, SD = .14, for ordered and random groups, respectively). The parallel ANOVA for walk time showed no effects.

Figures 4C–D show that the slope of the regression function, b, increased across sessions for both step number and walk time for all three groups. The ANOVA on step number comparing the three groups at sessions 1 and 10 revealed main effects for session, $F(1,22) = 23.13$, $p < .001$ (M = .11, SD = .10, and M = .22, SD = .14, for sessions 1 and 10, respectively), and group, $F(2,22) = 4.82$, $p < .05$ (M = .26, SD = .10, M = .15, SD = .08, and M = .13, SD = .08, for ordered, random, and control groups, respectively). Post-hoc comparisons confirmed greater values of b for step number in the ordered trial group than the random and control groups, all ps < .001. For walk time, the parallel ANOVA confirmed only a main effect for session, $F(1,22) = 11.69$, $p < .01$ (M = .06, SD = .06, and M = .11, SD = .07, for session 1 and 10, respectively). The ANOVAs comparing ordered and random groups across the 8 practice sessions produced no significant effects for step number and confirmed only a main effect for group for walk time, $F(1,11) = 5.16$, $p < .05$ (M = .13, SD = .02, and M = .08, SD = .05, for ordered and random groups, respectively).

Prospective Control While Approaching the Slope

A second set of questions concerned perceptual guidance of infants' gait modifications: Did infants respond prospectively by planning gait modifications before stepping over the brink or reactively by modifying their walking patterns only after they stepped onto the slopes? We examined prospective control by assessing step number, touching, and latency on the starting platform as infants faced easy and challenging slopes. We used the same analytic approach as with gait modifications on slopes: We included only the trials where infants walked successfully; we estimated a best fitting regression line for each infant and session to summarize the link between slope angle and the various response measures; and we used repeated measures ANOVAs to assess effects of practice across sessions 1 and 10. Repeated measures ANOVAs for step number, touching, and latency on the correlation and slope coefficients showed no effects for session or practice group. Rather, as shown in Figure 5, most infants displayed evidence of prospective control at the beginning of the study (as indicated by significant correlation coefficients, all ps < .05) and no evidence of further improvement.

At sessions 1 and 10, step number on the starting platform ranged from 0, if infants stepped directly onto the slope, to 25 if infants took many tiny forward, backward, or pivoting steps before stepping over the brink (*M* = 3.06). Across the 50 protocols at sessions 1 and 10, 66% showed significant positive correlations between step number and slope angle (average *r* = .42, *SD* = 0.21). In general, when infants increased step number on the starting platform, they also increased step number (average *r* = .28, *SD* = 0.25) and walk time on slopes (average *r* = .24, *SD* = 0.23).

Touching was a low frequency behavior on successful trials. Across the 50 protocols at sessions 1 and 10, infants touched slopes on only 14.84% of successful trials, and 6 protocols had no touch trials at all. Of the remaining 44 protocols, touching was positively correlated with step number (average *r* = .27, *SD* = 0.19), suggesting that infants took small steps to approach the brink in preparation of probing the slope with their feet. Touching was significantly positively correlated with slope angle for 41% of the protocols that included touching (average *r* = .33, *SD* = 0.20). Touching on the starting platform was positively correlated with step number (average *r* = .27, *SD* = 0.19) and walk time (average *r* = .24, *SD* = 0.22) on slopes.

Latency ranged from 0 s to 48.33 s across sessions. Latency included the time infants spent modifying their step length and touching, as well as time peering over the brink to explore slopes visually, and time in displacement activities such as calling to their caregivers. Latency was positively correlated with step number on the starting platform (average r = .77, SD = 0.15) and with touching (average r = .51, SD = 0.19). The correlation between latency and slope angle (average r = .34, SD = 0.19) was significant and positive for 46% of the protocols. Latency was positively correlated with step number (average r = .23, SD = 0.24) and walk time (average r = .22, SD = 0.24) on slopes.

Footfall Measures on the Starting Platform and Slope

Footfall patterns on the starting platform and slope provided a more direct measure of infants' step lengths on shallow and steep slopes. Figure 6 shows an overhead view of the walkway with the raw footprint data (symbols represent heel strikes) for each infant in the two practice groups (data from one child in the ordered trial group were missing due to fussiness). The first row of graphs represents data from the infant shown in Figure 3. The fourth infant shown in Figure 6 refused to descend the steep slope at 80% of his walking threshold, so his "steep slope" was 60% of his threshold instead.

As evident in the figure, infants' use of the braking strategy was prospective, not reactive. On the shallow slope, infants walked straight over the brink with large, evenly spaced steps. But on the steep slope, infants took multiple, tiny steps as they approached the top edge of the slope. To quantify infants' steps on the flat starting platform, we counted the number of steps within 61 cm of the top edge of the slope (demarcated by the dashed gray lines). A 2 (ordered and random groups) × 2 (shallow and steep slopes) ANOVA on step number prior to stepping over the brink confirmed a main effect for slope angle; $F(1,10) = 46.51$, $p < .001$. Infants took more steps before stepping onto steep slopes (*M* = 6.92, *SD* = 2.19) compared with shallow slopes (*M* = 2.50, *SD* = 0.64).

Figure 6 also illustrates that every infant shortened his or her step length on the steep slope compared with the shallow one, especially at the top portion of the steep slope. We divided the slope in half and counted infants' steps at top and bottom. A 2 (ordered and random groups) × 2 (shallow and steep slopes) × 2 (top and bottom of the slope) repeated measures ANOVA on step number confirmed a main effect for steepness, $F(1,10) = 96.66$, $p < .001$, and for position on the slope, $F(1,10) = 22.82$, $p < .01$. Infants took more steps on steep (*M* = 5.06, *SD* = 1.47) than shallow (*M* = 2.10, *SD* = 0.47) slopes, and they took more steps at the top (*M* = 4.29, *SD* = 1.24) than the bottom (*M* = 2.88, *SD* = 0.75) portion of the slopes. Main effects were mediated by a group × steepness interaction, $F(1,10) = 7.32$, $p < .05$, and a steepness × position interaction, $F(1,10) = 25.99$, $p < .001$. Infants in the random trial group ($M = 5.79$, $SD = 1.50$) took slightly more steps on steep slopes compared to the ordered trial group ($M = 4.05$, $SD = 0.57$); $p < .01$. On steep slopes, infants took more steps on the top ($M = 6.50$, $SD = 2.22$) than on the bottom ($M = 3.63$, $SD = 1.03$) portion of the slope, $p < .001$.

Discussion

Extreme variations in terrain require infants to select the appropriate locomotor action. For example, on impossibly steep slopes, infants must decide whether to walk, slide, or avoid descent. More subtle variations in terrain require a different sort of perception-action coupling: Infants can continue to walk if they modify their ongoing gait patterns appropriately. The current study expanded on previous work showing that experienced walking infants select actions adaptively under extreme variations in slope angle (reviewed in Adolph, 2002, 2005). Here, we examined changes in infants' ability to modify ongoing gait patterns in accordance with more subtle variations in slope angle. In particular, we assessed infants' use of a braking strategy to curb the buildup of walking speed on increasingly steeper slopes. We documented change in perception-action coupling at three nested time scales. Within trials, we examined infants' behaviors before and after stepping over the brink to determine whether gait modifications are planned prospectively. Within sessions, we summarized infants' behaviors with individual functions across the levels of difficulty imposed by increasing slope angles. And across sessions, we documented effects of practice walking down slopes using a microgenetic training design.

Evidence for a Braking Strategy

Relying on video recordings and footfall measures, we sought evidence for a braking strategy with increase in step number (corresponding to shortening average step length) and/or walk time (corresponding to increase in average step time). Adults curb progressive buildup of walking speed by shortening their step length and slightly decreasing walk time to maintain the same walking speed relative to flat ground (Leroux et al., 2002; Redfern & DiPasquale, 1997). As in previous work (Adolph & Avolio, 2000), infants in the current study increased their step number, but also increased their walk time relative to flat ground. At sessions 1 and 10, every infant showed a significant increase in both step number ($M = 8.52$, $SD = 1.45$) and walk time ($M = 3.37$, $SD = 0.85$) on slopes steeper than 4° compared with 0° to 4° slopes ($M = 5.89$, $SD = 0.68$ and $M = 2.13$, $SD = 0.70$ for step number and walk time, respectively); all ps $< .001$. Unlike adults, infants may lack the necessary balance control and strength to maintain flat ground walking speed while walking down slopes. With small, fast steps, infants would essentially bounce down the steeper slopes. Thus, they may need to adjust both parameters to ensure sufficient braking. Indeed, the footprint data illustrated in Figure 6 showed that infants exerted more control at the top portion of the slope and then relaxed step length (and presumably step time) toward the bottom portion of the slope where they could catch themselves on the landing platform.

Implementing a braking strategy requires both the physical wherewithal to modify walking patterns and coupling between perception and action to link gait modifications with variations in slope angle. At session 1, infants already displayed the physical wherewithal to modify gait patterns: Average maximum step number ($M = 21.00$ steps) and walk times ($M = 10.83$ s) were impressively high. The infant shown in Figure 3, for example, had 5 trials with ≥ 15 steps and 3 trials with walk times ≥ 6 s. Nonetheless, use of the braking strategy was not connected systematically to slope angle, and infants sometimes resorted to running down steeper slopes. By session 10, physical wherewithal was translated into adaptive action. Gait modifications were finely attuned to variations in slope angle. Correlation and slope coefficients increased, indicating more consistent and pronounced responding to slope angle.

Ironically, the shift from larger, faster steps at session 1 to smaller, slower steps at session 10 runs counter to 100 years of research on the development of infant walking. Traditionally, improvements in infant walking are associated with increases in step length and velocity (Adolph et al., 2003; Bril & Breniere, 1992; Garciaguirre, Adolph, & Shrout, 2007). However, in traditional laboratory assessments, infants walk over a flat, uniform, uncluttered path. In less artificial situations, when the ground surface is slanting, slippery, narrow, or obstructed, walkers must take smaller, slower steps to dampen propulsive forces that might lead to falling (Cham & Redfern, 2002; Patla, Prentice, Robinson, & Neufeld, 1991). What made small, slow steps indicative of more advanced walking skill is that infants produced these gait modifications on purpose by drawing on the full range of their walking abilities, rather than inadvertently because of limited walking skill.

Evidence for Prospectivity

Prospective control of gait modifications would provide further evidence to support the contention that small, slow steps can reflect improvements in perceptual guidance of motor action. The video data provided one source of evidence that gait modifications were planned prospectively on the starting platform, rather than reactively after receiving feedback mid-slope for prospective control. Step number, touching, and latency increased with larger slope angles, suggesting that infants used visual information about slope angle to guide exploration on the starting platform, and each variable was positively associated with step number and walk time on slopes. In previous work, the association between slope angle and touching and latency on the starting platform may have been driven by inclusion of impossibly steep slopes and trials where infants refused to walk (Adolph, 1995, 1997; Adolph & Avolio, 2000; Tamis-LeMonda, Adolph, Lobo, Karasik, & Dimitropoulou, 2008). By excluding unwalkable slopes and refusal trials, the current study shows that touching and latency were not prompted only by the necessity of selecting an alternative method of locomotion. Rather, infants must have recognized the increasing challenge of steeper slopes in the walkable range.

We found no evidence of a session effect to suggest that prospective control increased with practice or walking experience. Rather, for many infants, correlations between behaviors on the starting platform and slope angle were robust at session 1. Given that gait modifications on slopes increased from session 1 to 10, infants may have learned to link their existing sensitivity to variations in slope angle with the gait modifications that best control increases in walking speed.

The footprint data provided a second source of evidence for prospectivity. As illustrated in Figure 6, infants decreased their step length before stepping over the brink of steep slopes, but not before walking down shallow slopes. On steep slopes, steps bunched into tight clusters before the brink, and on shallow slopes, steps were evenly spaced over the starting platform and slanted section of the walkway. Possibly, prospective gait modifications aid in the implementation of the braking strategy by minimizing forward momentum and keeping infants' bodies in a more upright position. Moreover, step length on steep slopes was shorter near the top of the slope and larger toward the landing platform. The opposite pattern—larger steps at the top of the slope and smaller steps at the bottom—was not found, suggesting that infants do not have the strength and balance to decide reactively to implement the braking strategy in the midst of running down the slopes.

Evidence for Learning

At session 1, infants were impressively savvy about coping with slopes. As in previous work (e.g., Adolph, 1995, 1997), they refused to walk down impossibly steep slopes. Expanding on previous work (Adolph et al., 2000), they showed evidence of prospective planning even on walkable slopes. And like the 14-month-olds in Adolph and Avolio's (2000) experiments, the 15-month-olds in the current study displayed the ability to modify their gait patterns while walking down slopes. However, use of the braking strategy improved dramatically between sessions 1 and 10, so that step number and walk time were geared more closely to changes in slope angle as revealed by significant increases in correlation and slope coefficients.

One of our aims was to document the course of learning across training sessions as well as pre- and post-test sessions. Whereas previous work showed steady, gradual learning curves for selecting motor actions on slopes (Adolph, 1997), the trajectories for learning to modify walking patterns were sharp and rapid (see Figure 4), resembling the sort of power functions that typically characterize motor skill learning in general (e.g., Schmidt, 1975) and development of walking in particular (e.g., Adolph et al., 2003). In fact, rapid learning from practice on slopes in session 1 may explain, at least in part, the surprising finding that infants in the control group showed similar performance to infants in the practice groups at session 10. Possibly, infants in the control group needed only a few dozen trials walking down slopes at session 1 to better gear their gait modifications to the changes in slope angle at session 10.

The puzzling finding of improvements in the control group may also be explained by learning from walking experience in other contexts and age-related changes in walking proficiency. Several lines of evidence support this contention. The control group showed equally strong improvements in walking thresholds between sessions 1 and 10, indicating that walking proficiency improved at similar rates to the practice groups. Infants of a similar age and level of walking experience to the control group at session 10, displayed gait modifications without practice in other contexts: On their first encounter with bridges of varying widths, they decreased step length and walking speed to walk over narrow bridges compared with wide ones (Berger & Adolph, 2003; Berger, Adolph, & Lobo, 2005). Finally, the 23 days of everyday walking experience between sessions 1 and 10 reflect a tremendous amount of practice. The average 14-month-old, for example, takes over 2,000 steps per hour during free play (Adolph, Badaly, Garciaguirre, & Sotsky, 2008). In the current study, infants in the ordered and random trial groups averaged only 8.13 steps per trial and accumulated only 1,379.50 steps on slopes across the 8 practice sessions.

Another aim was to examine the effects of ordered and random practice regimens. As illustrated in Figure 4, infants in the ordered trial group benefited from organized trial presentation for several outcome measures. Based on the video data, ordered practice resulted in larger correlation coefficients between step number and slope angle over the 8 practice sessions, larger slope coefficients at sessions 1 and 10 for step number, and larger slope coefficients over the 8 practice sessions for walk time. Although the footprint measures showed slightly more steps on steep slopes in the random trial group, we were not able to use the footprint method to compare change in gait modifications across a variety of slope angles for each infant. Presumably the footprint measures would have confirmed greater attunement between step number and slope angle in the ordered trial group. A likely explanation is that the ordered practice regimen scaffolded infants' responses, by gradually increasing and decreasing the difficulty of consecutive slope angles. In contrast, with the random trial practice regimen, the previous trial was likely to be dissimilar to the next one, forcing infants to assess each slope angle with a fresh eye. Thus, for the ordered trial group, the previous trial served as practice for the succeeding trial, and as a reminder about how best to cope with a similar slope.

A final point is noteworthy: Infants learned the braking strategy spontaneously. Gait modifications were not obligatory; infants were presented with a target range of slope angles normalized to their current walking abilities such that their typical walking patterns were sufficient for safe descent. Rate of falling was not a motivator; there were no differences in the number of trials scored as failures at any session and no increase in gait modifications on trials that followed a fall. We simply presented infants with the opportunity to learn the relations between degree of slope, various walking patterns, and the consequences for maintaining balance. And they learned it.

Conclusions: Change in Action

One of the great advantages of using motor actions to understand learning and development is that changes are readily apparent over multiple, nested time scales. By describing changes in gait modifications across sessions, degrees of slope, and the progression of steps within a trial, the current study suggests how infants may have succeeded at linking a behavior in their repertoire to perceptual information about the changing status of the environment. Small, slow steps were always in infants' repertoires. What was missing was the ability to apply those gait patterns systematically in response to changing slope angles. Learning to do so emerged after repeated opportunities to relate the sight and feel of a slope with perceptual feedback about the consequences for balance and gait. Consistent with Whiting's (1984) description of motor learning in adults, our data indicate that the development of perception-action coupling required for fine-tuning ongoing action in infants builds on the earlier developing ability to select the appropriate action.

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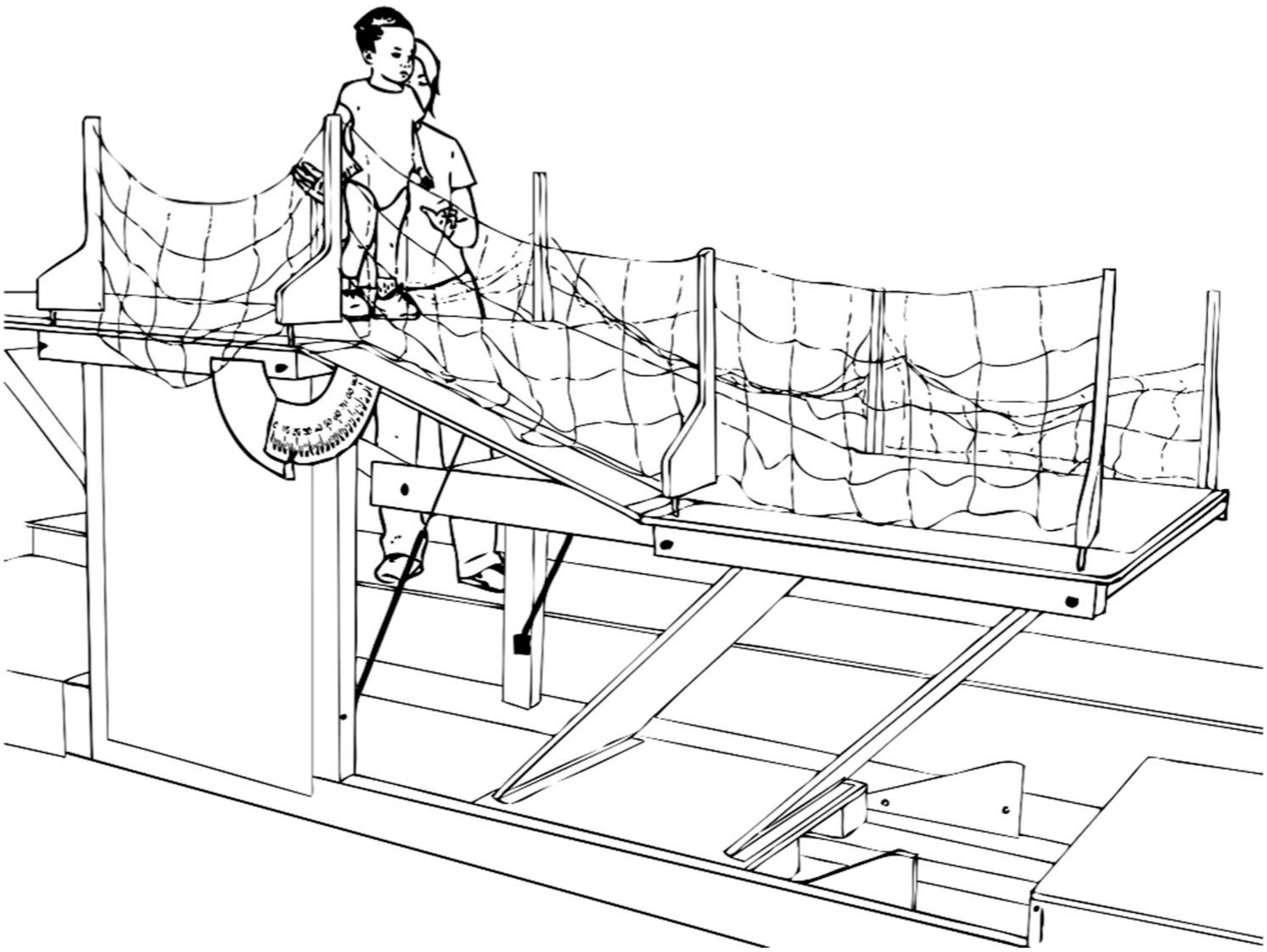

Figure 1.
Adjustable sloping walkway. Slope angle can be adjusted in 1°-increments from 0° to 90°. To ensure infants' safety, nets lined the sides of the walkway and an experimenter followed alongside infants. Caregivers (not shown) encouraged infants from the bottom of the landing platform.

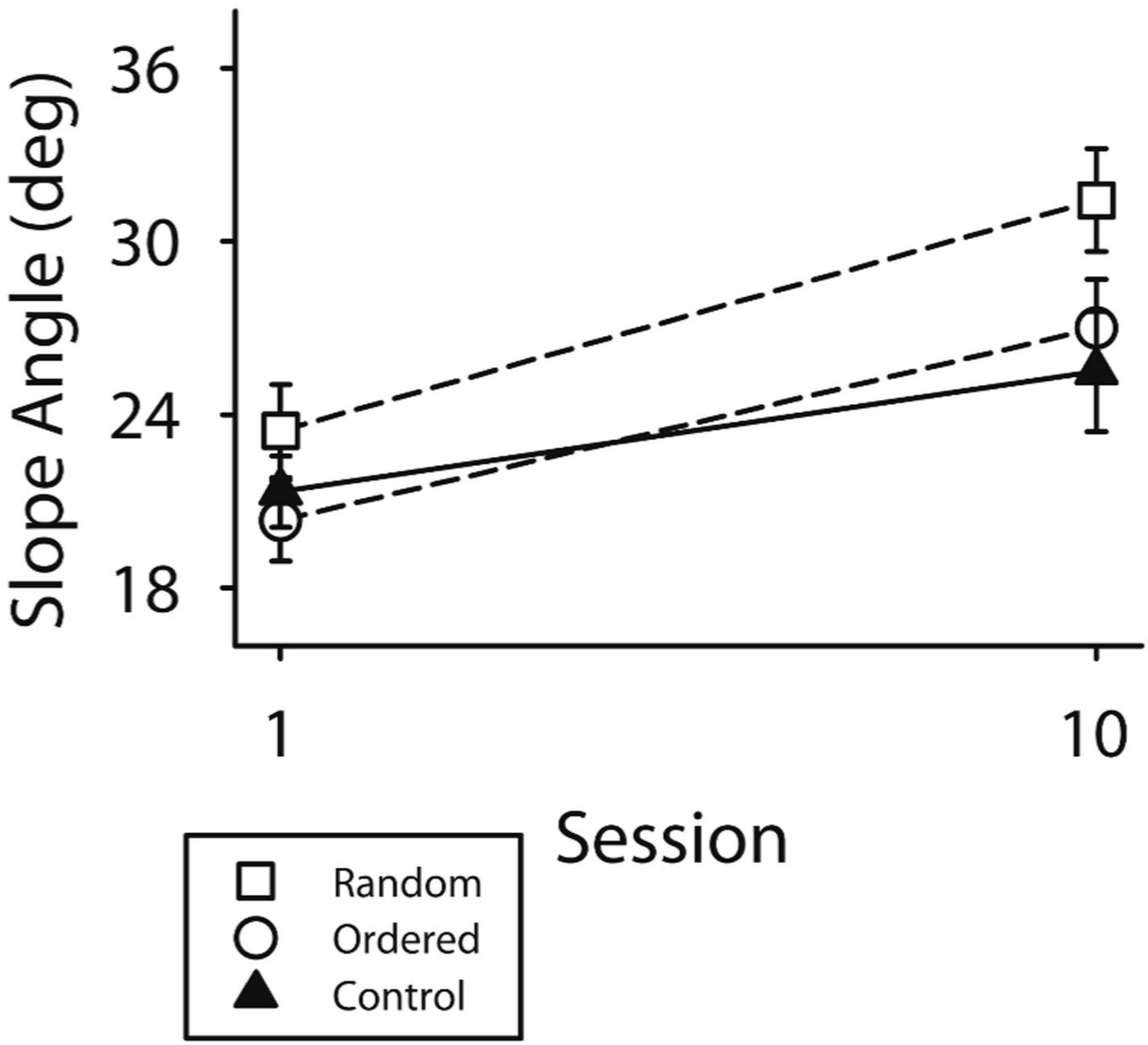

Figure 2.

Average walking thresholds at sessions 1 and 10. Open circles and the dashed line represent the ordered trial group, open squares and the dashed line represent the random trial group, and filled triangles and the solid line represent the control group. Error bars denote standard errors.

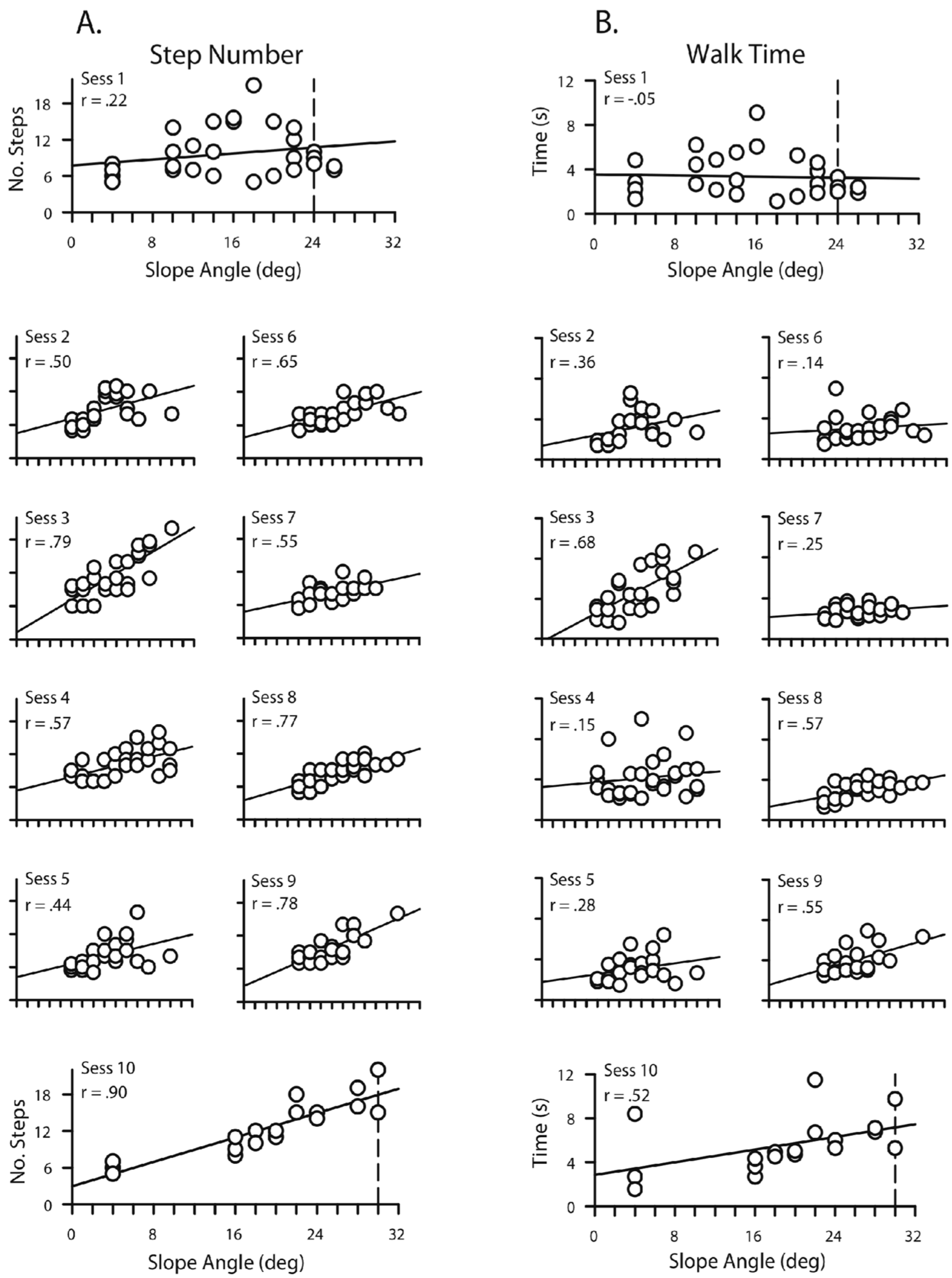

Figure 3.

Example of one infant's gait modifications under an ordered trial practice regimen at each session on all slopes. Note, at session 10, the walking threshold increased from 24° to 30° (thresholds depicted by dashed vertical lines). Step number is depicted on the left columns of graphs and walk time is depicted in the right columns. Each symbol represents the result of one trial. Correlations with the slope angle are located in the upper left corner for each session.

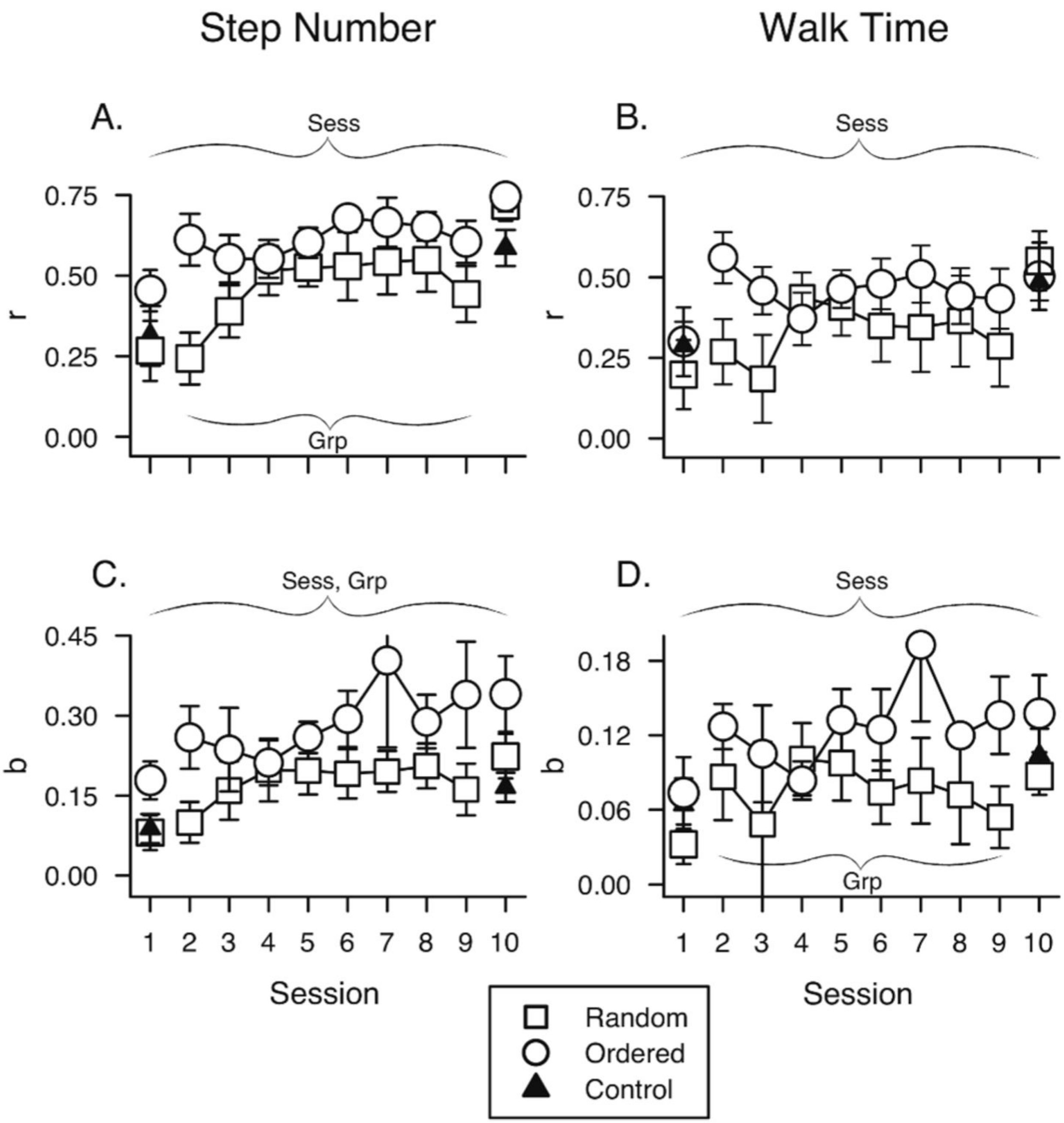

Figure 4.

Average data for each group at every session on all slopes. Open circles represent the ordered trial group. Open squares represent the random trial group. Filled triangles represent the control group. (A) Correlations (*r*) between slope angle and step number and (B) between slope angle and walk time. (C) Regression coefficients (*b*) for step number and (D) walk time. Data at session 10 reflect the increase in infants' average walking thresholds from session 1 (M = 21.68°) to session 10 (M = 27.52°). Error bars depict standard errors.

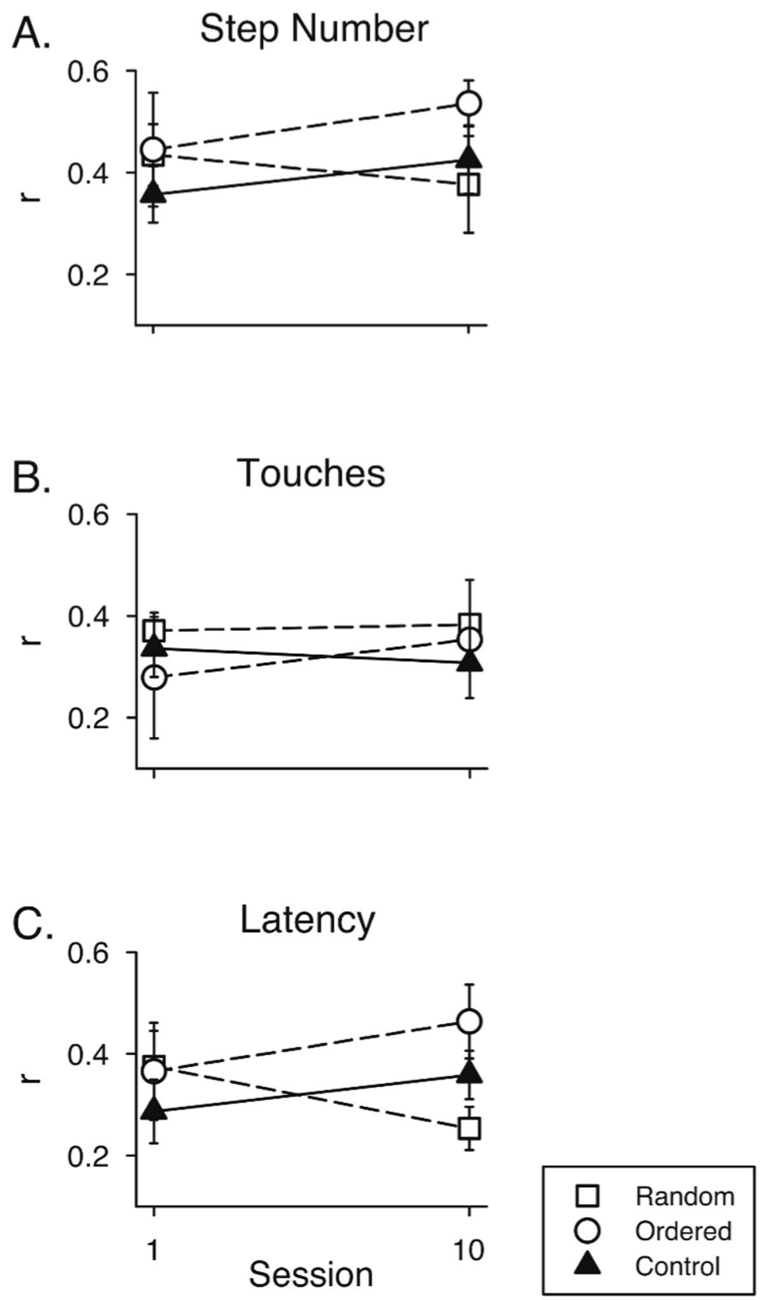

Figure 5.
Average exploratory behaviors at sessions 1 and 10. Open circles and the dashed line represent the ordered trial group. Open squares and the dashed line represent the random trial group. Filled triangles and the solid line represent the controls. Correlations (*r*) (A) between slope angle and steps taken on the starting platform, (B) between slope angle and foot touches at the brink of the slope, and (C) between slope angle and latency. Error bars denote standard errors.

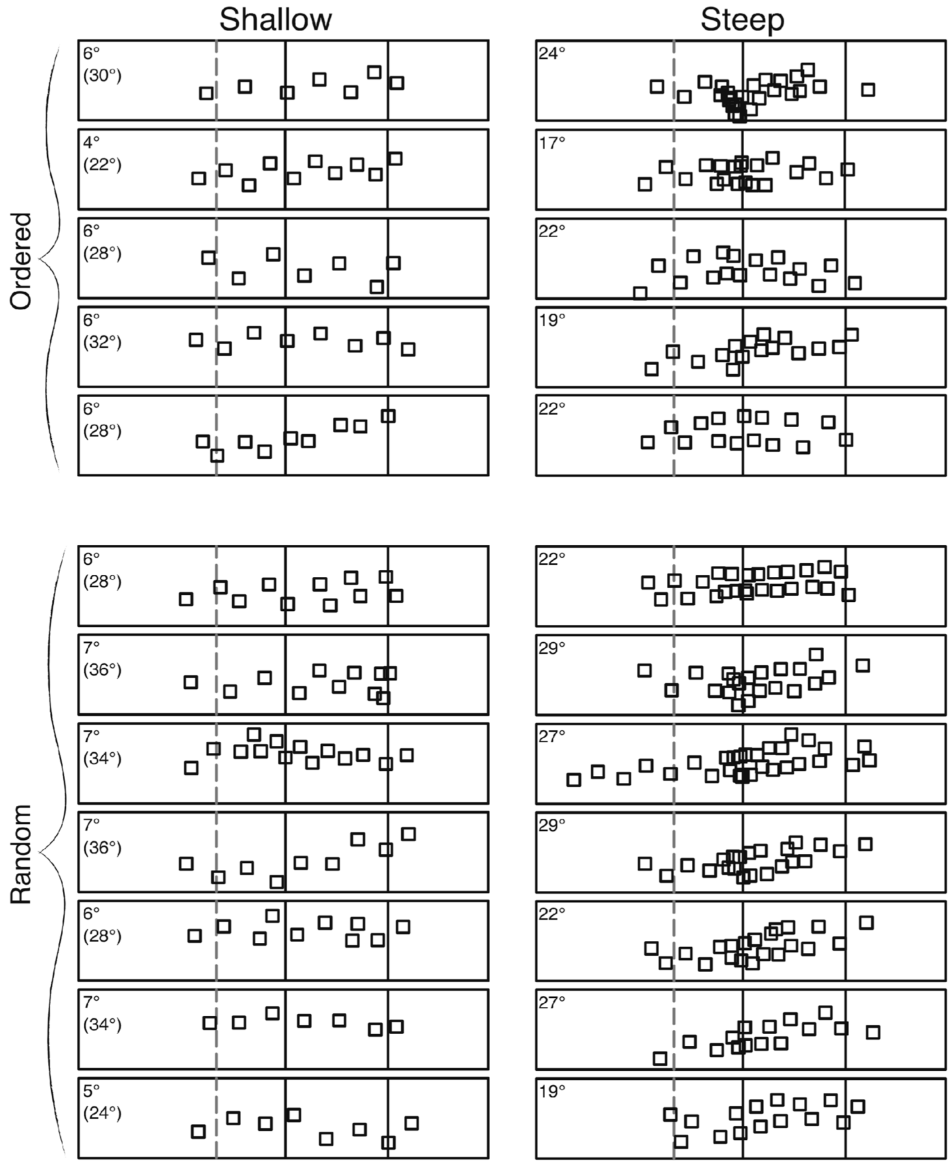

Figure 6.

Footprint data on one shallow (20% of session 10 threshold) and one steep (80% of session 10 threshold) for each infant in the two practice groups. Each graph represents an overhead view of the sloping walkway. Solid vertical lines demarcate portions of the walkway. The leftmost portion represents the flat starting platform. The middle section represents the slope. The rightmost portion represents the flat landing platform. Therefore, the direction of infants' walking progressed from left to right. The dashed gray line depicts the portion of the starting platform that is 24 inches away from the brink of the slope. Each row represents data for one infant and each symbol represents a step. Infants in the ordered trial group are shown on the top half of the page (one infant did not contribute data). Infants in the random trial group are shown on the bottom of the page. Numbers in the top left corner of the graphs indicate the shallow and steep slope angles. Degrees were rounded to the nearest whole number after shallow and steep slope angles were calculated. Note that the fourth infant in the ordered trial group walked on a steep slope angle at 60% of the threshold due to a refusal at the steep 80%

threshold slope angle. Numbers in parentheses show each infant’s walking threshold at session 10.

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