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Bridging the Gap: Solving Spatial Means–Ends Relations in a Locomotor Task

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Using a means–means–ends problem-solving task, this study examined whether 16-month-old walking infants (N = 28) took into account the width of a bridge as a means for crossing a precipice and the location of a handrail as a means for augmenting balance on a narrow bridge. Infants were encouraged to cross from one platform to another over narrow and wide bridges located at various distances from a wooden handrail. Infants attempted to walk over the wide bridge more often than the narrow one and when the handrail was within reach. Infants demonstrated parallel problem solving by modifying exploratory behaviors and bridge-crossing strategies that simultaneously accounted for the spatial and functional relations between body and bridge, body and handrail, and bridge and handrail.

Means–ends problem solving is an important cognitive and motor achievement. It requires coordinating environmental supports with relevant body parts to extend the body's capabilities and monitoring multiple spatial and functional relations between actor, goal, and means. Pulling a cane to retrieve an out-of-reach toy, for example, requires recognition that the toy is beyond arm's reach and that a cane could extend the body's limits, implementation of an appropriate grasp of the handle, and understanding that the toy must be positioned inside the crook of the cane (e.g., Chen & Siegler, 2000; McCarty, Clifton, & Collard, 2001; van Leeuwen, Smitsman, & van Leeuwen, 1994). Changing frames of reference present a challenging ''localization problem'' (Lockman, 2000). Even preschoolers err in simple object-retrieval and spoon tasks after a change in the spatial relations between hook and toy or between hand and spoon (Smitsman & Cox, 2008). Task difficulty is compounded in *means–means*–ends tasks because the goal is so removed that multiple means must be employed to attain it (Santos, Rosati, Sproul, Spaulding, & Hauser, 2005). Multiple means may be implemented sequentially, as in using a short stick to rake in a longer stick, which could then be used to retrieve a distant toy, or in parallel, as in standing on a step stool while wielding a pole to reach a distant object (McGraw, 1935).

Typically, researchers study means–ends problem solving in infants by assessing their ability to use manual tools to retrieve an out-of-reach object and focusing on spatial relations between the actor, tool, and goal (e.g., Connolly & Dalgleish, 1989; Smitsman & Cox, 2008; Sommerville & Feldman, 2008; Steenbergen, van der Kamp, Smitsman, & Carson, 1997). A recent series of experiments took a different approach (Berger & Adolph, 2003; Berger, Adolph, & Lobo, 2005). The task involved the whole body, not just the hands, and we focused on means–means–ends problem solving rather than simple means–ends problem solving: To reach a goal at the other side of a deep precipice, infants had to recognize that a bridge could serve as a means for crossing and that a handrail could serve as a means for augmenting balance on narrow bridges. The spatial challenges of such bridge–

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handrail tasks require that the various body parts be coordinated with the location of the relevant environmental supports.

The bridge–handrail task requires a parallel means–means–ends solution. The body simultaneously links multiple elements—the feet balanced on the bridge and the hands grasping the handrail—as means for crossing the precipice. Such parallel coordination poses special problems because monitoring the top and bottom of the body simultaneously takes months to develop. Eleven-month-old cruising infants, for example, do not monitor their feet moving along the ground at the same time that they monitor their hands holding onto furniture for balance (Adolph, Berger, & Leo, in press). Although cruisers can see and feel their feet approaching a precipice, with their hands gripping a sturdy handrail, they step over the brink and fall. In contrast, 16-month-old walkers modify their crossing strategies on medium-sized bridges by slowing down, taking smaller steps, and turning sideways. To cross narrow bridges, they hang onto a sturdy handrail to augment balance. When bridges are impossibly narrow but no handrail is available, infants refuse to cross (Berger & Adolph, 2003). With only a wobbly handrail, they enhance balance control by pulling backward on the wobbly rail like a mountain-climbing rope (Berger et al., 2005).

Current Study

The current study focused on the complex spatial problems involved in the development of means–means–ends problem solving. We examined infants' ability to perceive the spatial relations among actor, goal, and two means in a new bridge–handrails task. We challenged 16-month-olds to cross bridges of varying widths located at various distances from a handrail. Infants had to monitor whether their bodies fit on the bridge, whether they could reach the handrail with their hands while their feet were on the bridge, and whether modification of handrail-use or bridge-crossing strategies would enable safe crossing. By varying bridge–handrail proximity, infants had to cope with the spatial relation between the two means for crossing the precipice. We expected greater success on wider bridges and when the handrail was in appropriate proximity to the bridge. We predicted that infants would devise strategies for crossing the bridges, but on narrow bridges far from the handrail, crossing would be impossible.

Method

Participants and Procedure

Twenty-eight infants (13 boys) were recruited through a commercial mailing list of families living in the New York City area. All were 16 months old (± 1 week) and born at term; most were White and middle class. In a structured interview (Adolph, Vereijken, & Shrout, 2003), parents reported the 1st day that infants walked independently 10 ft across a room. Walking experience ranged from 25 to 175 days ($M = 104.36$ days). Infants received a souvenir for participating.

Figure 1 shows the wooden bridge–handrail apparatus with starting and finishing platforms flanking a large precipice (Berger & Adolph, 2003; Berger et al., 2005). A 16- or 36-cm-wide bridge spanned the precipice and could be quickly changed between trials. A handrail ran parallel to the bridge. The bridge was placed at one of three locations relative to the handrail: flush, middle, and far, with the nearest edge of the bridge 0, 20.5, or 40 cm from the edge of the handrail, respectively. Previous work suggested that most infants would not require a handrail on the 36-cm bridge but would on the 16-cm bridge.

After infants were acclimated to the walkway, each bridge was presented twice at each location for a total of 12 trials. Six presentation orders were counterbalanced across sex. Infants began trials standing upright on the starting platform. Trials ended when infants crossed, fell, or remained on the starting platform for 45 s. Trials were videotaped with side and overhead views mixed onto a single video frame. After testing on the walkway, an experimenter measured infants' height, weight, and arm span. Sessions lasted approximately 60 min.

Data Coding

Data were coded from videotapes using MacSHAPA, a computerized video coding system (OpenSHAPA.org; Sanderson et al., 1994). A primary coder scored 100% of trials. To ensure interrater reliability, a secondary coder scored 25% of each infant's trials. For categorical and frequency measures, we calculated the proportion of trials that the two coders were in agreement. Interrater reliability ranged from .97 to 1.0; p values for all Cohen's Kappa coefficients < .01. For measures of duration, we calculated the correlation between coders' scores. Correlation coefficients ranged from $r = .98$ to $r = 1.0$. Only 2% of reliability trials

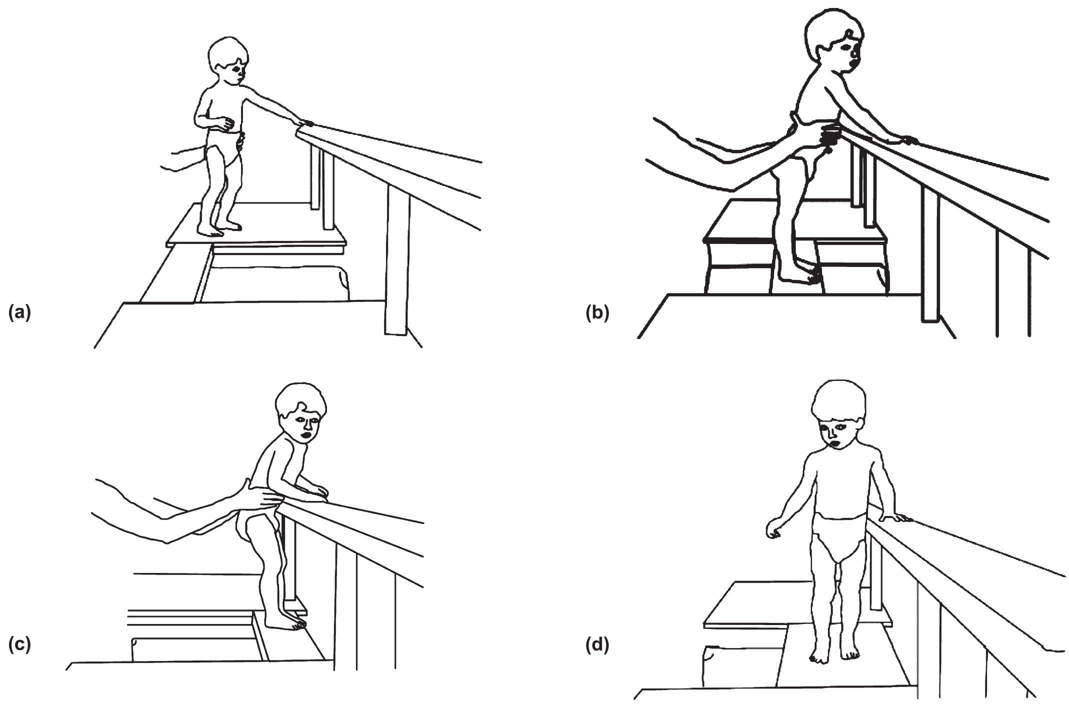

Figure 1. Walkway with varying bridge widths and handrail locations spanning a precipice (76.2 cm long × 76 cm wide × 74 cm deep) lined with 13.5 cm of foam padding along the sides and bottom. Apparatus is shown with (a–c) 16-cm and (d) 36-cm bridges at (a) far, (b) middle of the walkway, and (c,d) flush with the handrail locations.
Note. Caregivers (not shown) stood at the far end of the finishing platform (157 cm long × 76 cm wide × 86 cm high) and encouraged infants to cross by offering toys and cereal but did not draw infants' attention to the handrail or provide instructions. An experimenter (partially visible) followed alongside infants to ensure their safety. An assistant (not shown) adjusted the bridges and switched the handrails. To keep infants motivated, an easy, baseline 72-cm wide bridge was presented after each block of three trials.

resulted in discrepancies; these were resolved through discussion.

Crossing behaviors. Coders scored attempts to walk over the bridge (stepped onto the bridge with both feet) as successful if infants walked from one platform to the other without falling. Coders documented body position (facing forward, turned sideways) as infants stepped onto the bridge, whether they used the handrail (touched with ≥ 3 fingers for ≥ 0.5 s after stepping onto the bridge), and how they used the handrail (five combinations of body/arm positions). For successful attempts, coders measured number of steps to cross.

Exploration prior to embarking. Latency to step onto the bridge (from the moment that infants were released by the experimenter and faced the bridge or finishing platform until they stepped onto the bridge) included time spent in exploration and in displacement activities such as calling to the caregiver. Apparatus exploration included touching the handrail or bridge for ≥ 0.5 s before stepping onto the bridge. Exploration of the distance between bridge and handrail included shifting back and forth between bridge and handrail at least once in the same trial or gesturing toward the handrail by extending the arms while standing in front of the bridge.

Walking skill. To estimate infants' walking skill, average step length was calculated from videotape by dividing the distance between 2 points on the full walkway by the number of complete steps to walk from one point to the other.

Results

Attempts to cross, body position while crossing, and exploratory behaviors were analyzed with 2 (bridge width) × 3 (bridge location) repeated measures analyses of variance (ANOVAs). Main effects and interactions were followed by contrasts comparing each pair of locations for the two bridge widths and paired t tests comparing the two bridge widths at each of the three locations for a total of nine comparisons. A Bonferroni-adjusted alpha level corrected for experiment-wise error rates (overall p = .05).

Because so few infants attempted to cross the 16-cm bridge at the far location, we could not conduct repeated measures ANOVAs on infants' behaviors once they were on the bridge. Instead, we ran a series of planned comparisons for success rate, number of steps to cross the bridge, handrail use, and strategies for using the handrail.

Five children were missing either the 16-cm/middle or 36-cm/far width/location combination. These infants still received 12 trials total, but other trials were substituted due to experimenter error, for a total of 336 trials in the data set. Consequently, the number of participants included in repeated measures analyses was reduced from 28 to 23. The number of available trials was reduced for some measures because portions of trials were momentarily obscured from the camera view.

Crossing Behaviors

Infants attempted to walk over bridges on 72% of trials. An ANOVA on attempts to cross confirmed main effects for bridge width and bridge location (row A, Table 1; see Table 1 for all *F* and *p* values). Post hoc analyses revealed that infants attempted to cross the 36-cm bridge more often than the 16-cm bridge and attempts were less frequent when bridges were far from the handrail (all *p*s ≤ .03; total height of bars in Figure 2a). Successful bridge crossings (striped regions in Figure 2a) were frequent on the 36-cm bridge at all locations but limited largely to the flush and middle locations on the 16-cm bridge (59% and 66% of attempts, respectively). Planned paired samples *t* tests on successful attempts revealed differences between the 16- and 36-cm bridges at all bridge locations (all *p*s < .01) and revealed that infants were more successful when the 16-cm bridge was at the middle than far location, $t(7) = 2.97$, $p < .03$.

Infants' modification of bridge-crossing and handrail-use strategies took into account the spatial relations between their bodies, the bridge, and the handrail. An ANOVA on proportion of trials that infants turned their bodies sideways to fit onto the bridge revealed main effects for bridge width and bridge location (row B, Table 1). Infants most frequently faced forward and put one foot in front of the other while crossing bridges (sparse striped and dotted regions of Figure 2a) but were likely to turn sideways, sliding one foot behind the other, when the bridge was narrow and when the bridge was in the flush or middle positions (dense striped and dotted regions of Figure 2a). At each location, infants walked forward on the 36-cm bridge more often than on the 16-cm bridge, all *p*s < .05. As with attempts and successes, infants also walked forward over the 16-cm bridge more often at the middle location than at the other locations (all *p*s < .01). We had assumed that the flush position would be most conducive for walking, and this was the arrangement in our previous studies. However, the narrow space of the flush position forced infants' bodies against the handrail and limited the number of effective whole-body solutions. The middle bridge location gave infants room to maneuver their bodies, leaving the handrail accessible.

On successful trials, infants took more steps to cross the 16-cm bridge than the 36-cm bridge at both middle and flush locations, all *p*s < .01 (Figure 2b). Only 3 infants successfully crossed the

Table 1
Main Effects and Interactions of Bridge Width and Handrail Location on Infants' Bridge-Crossing and Exploratory Behaviors

	Main effect width		Main effect location		Interaction width/location	
Outcome measure	*F*(*df*)	*p* value	*F*(*df*)	*p* value	*F*(*df*)	*p* value
Crossing behaviors						
A. Attempts	39.64(1, 22)	< .01	9.22(2, 44)	< .01	*ns*	
B. Body position	10.96(1, 22)	< .01	6.56(2, 44)	< .01	*ns*	
Exploratory behaviors						
C. Latency to step onto bridge	64.92(1, 20)	< .01	11.07(2, 40)	< .01	*ns*	
D. Touching handrail	31.04(1, 22)	< .01	22.44(2, 44)	< .01	5.92(2, 44)	< .01
E. Touching bridge	13.04(1, 22)	< .01	*ns*		*ns*	
Gauge distance between bridge and handrail						
F. Body shifts	27.39(1, 22)	< .01	15.74(2, 44)	< .01	9.70(2, 44)	< .01
G. Gestures toward handrail	14.72(1, 22)	< .01	*ns*		3.83(2, 44)	< .03

Note. Effect size for all main effects with $p < .01 = .53$. Effect size for main effect with $p < .03 = .47$.

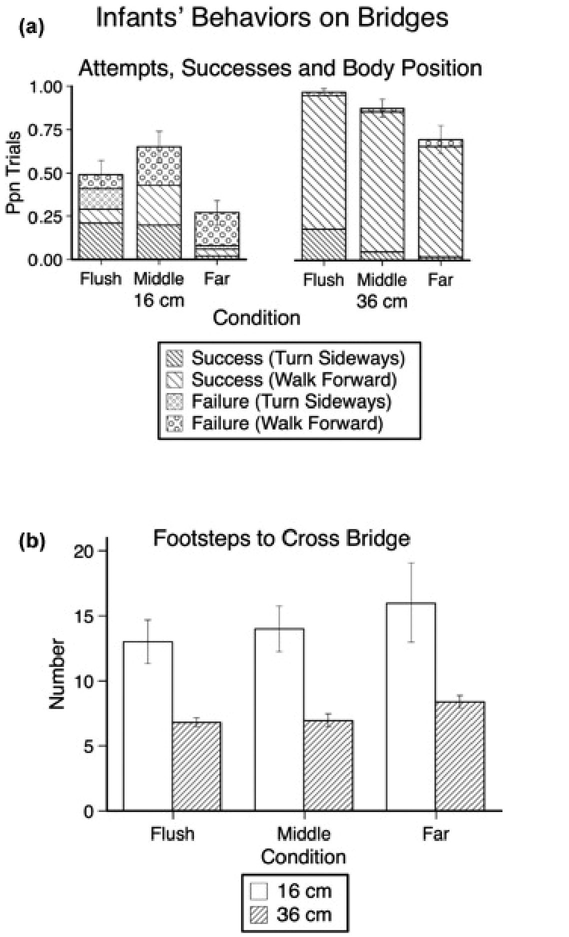

Figure 2. Effects of bridge width and bridge location on locomotor behaviors. (a) Proportion of trials infants attempted to walk, categorized by success and body position while crossing. (b) Number of footsteps infants took to walk over the bridge.
Note. Only 3 infants crossed the 16-cm bridge at the far location. Error bars denote standard errors.

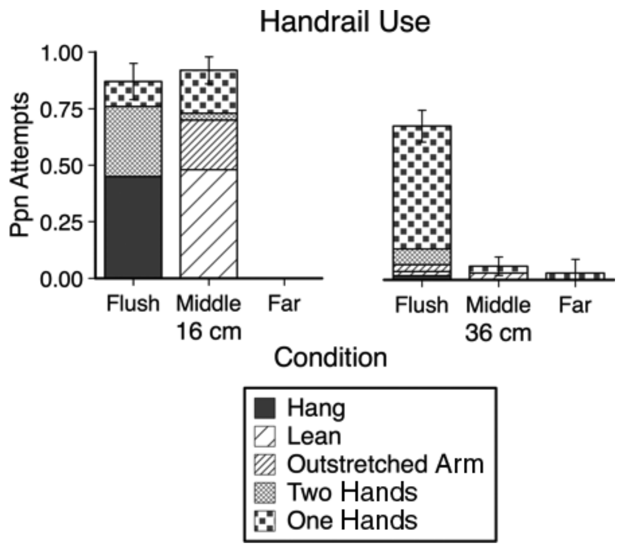

Figure 3. Proportion of attempted trials that infants used the handrail and their strategies for using the handrail at each bridge width/location combination.
Note. Infants could execute more than one type of strategy per trial but did not receive credit for performing the same strategy more than once per trial. Error bars denote standard errors.

16-cm bridge when it was far from the handrail, so analyses including that condition could not be performed. Location did not influence the number of steps to cross the 16-cm bridge. However, infants took more steps to cross the 36-cm bridge when it was far from the handrail than when it was flush with the handrail or in the middle of the walkway, $t(17) = 2.72$, $p = .01$ and $t(17) = 2.55$, $p = .02$, respectively.

Twenty-six infants used the handrail at least once. On the 90 trials when infants used the handrail, they held the handrail as they embarked or immediately after (within 2 s) stepping onto the bridge 65.6% of the time, suggesting that they coordinated both means in parallel prior to crossing. Planned paired-samples *t* tests confirmed that on attempted trials infants used the handrail more often on the 16-cm bridge than the 36-cm bridge when bridges were in the middle of the walkway, $t(17) = 10.31$, $p < .01$ (Figure 3). On the 16-cm bridge, infants never used the handrail at the far location. Handrail use at flush and middle locations did not differ. On the 36-cm bridge, only 1 child on one trial used the handrail at the far location. Surprisingly, infants used the handrail more often at the flush than middle and far locations, $t(26) = 8.37$, $p < .01$, and $t(18) = 7.51$, $p < .01$, respectively, even though touching was unnecessary (infants successfully crossed the 36-cm bridge without handrail use at the middle and far positions and in previous work; Berger & Adolph, 2003). Flush touches were cursory taps with one hand, as if noting rather than needing the handrail. When infants needed the handrail as a means for keeping balance, their touches were extended and they leaned toward the rail with their whole body.

Rates of handrail use were similar for the 16-cm flush, 16-cm middle, and 36-cm flush bridges, but infants displayed five qualitatively different strategies for coordinating placement of their hands on the handrail and their feet on the bridge, depending on bridge width and location. On half of the 16-cm flush trials, infants fit on the bridge by pressing the handrail against their chest and draping their bodies and arms over the railing (solid region in Figure 3 and illustrated in Figure 1c). On the other half, they used both hands to hold on as they walked sideways facing the handrail with their arms bent (dense checked region in Figure 3). On the 16-cm bridge in the middle of the walkway, infants turned their bodies sideways, leaned forward at the waist, and grabbed the handrail with two outstretched hands (sparse striped region in Figure 3 and illustrated in Figure 1b) or they walked forward with an arm fully outstretched to the side (dense striped region in Figure 3). In contrast, on the 36-cm bridge at the flush location, infants lightly touched the handrail with one hand as they walked (Figure 3 sparse checked region and illustrated in Figure 1d). The duration of infants' touches on the 16-cm flush (2.7 s) and 16-cm middle (2.85 s) bridges lasted over twice as long as they did on the 36-cm flush bridge (1.29 s), indicating that infants clung to the handrail on the 16-cm bridge but quickly tapped the 36-cm bridge as they passed. Thus, infants invented strategies for surmounting the distance between the bridge and handrail that were tailored to the width of the bridge and the distance from the handrail.

Exploration of Spatial Configuration Prior to Embarking

Infants engaged in a variety of information-gathering behaviors before deciding whether to cross the bridge. The ANOVA on latency to step onto the bridge confirmed main effects for bridge width and bridge location (row C, Table 1). Post hoc comparisons revealed longer latencies on the 16-cm bridge than on the 36-cm bridge and longer latencies at the far location than at the flush or middle locations (all *p*s < .03; Figure 4a).

Exploratory touching of the handrail and bridge decreased on the wider bridge and as the bridge moved farther from the handrail (rows D and E, Table 1; Figure 4b). The ANOVA for handrail exploration confirmed main effects for bridge width, bridge location, and an interaction between the two factors; the ANOVA for bridge exploration showed only a main effect for location. Post hoc comparisons revealed more exploration of the handrails on the 16-cm bridge than the 36-cm bridge at all locations (all *p*s < .04) and more bridge

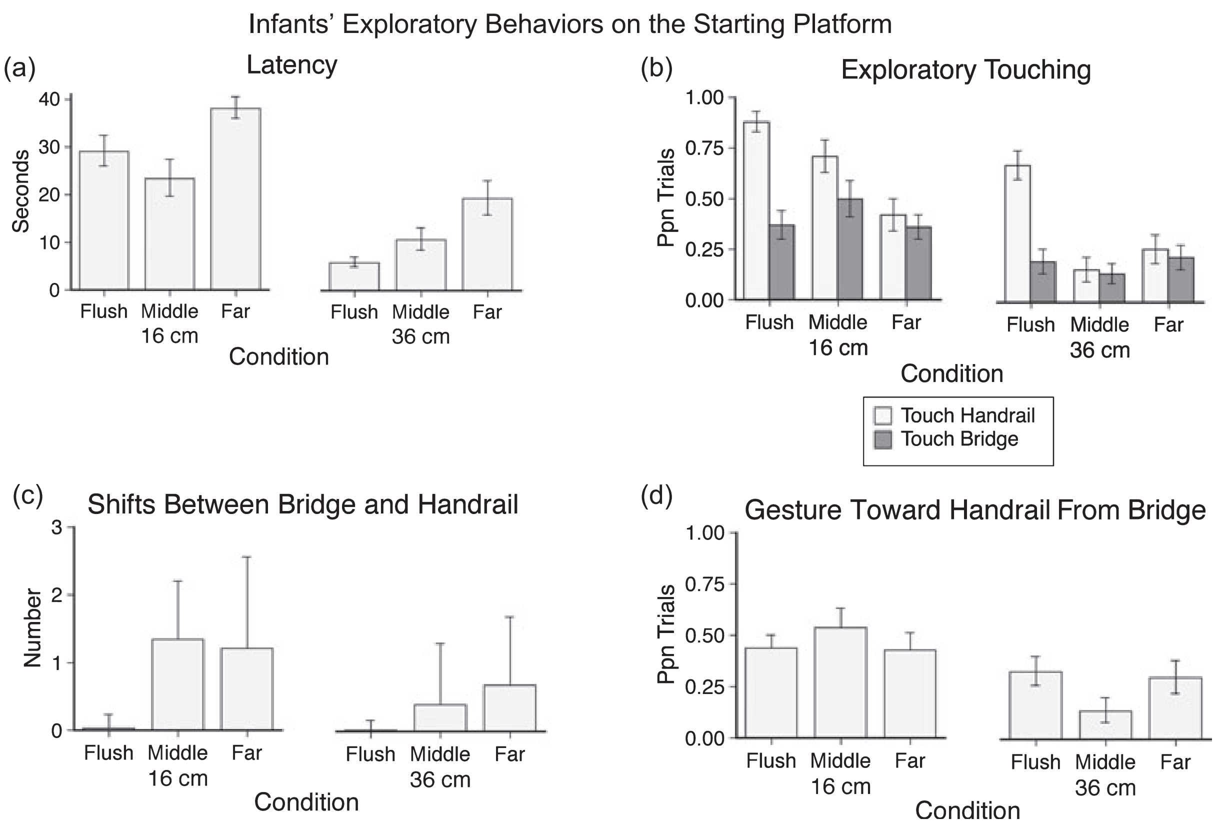

Figure 4. Effects of bridge width and bridge location relative to the handrail on exploratory behaviors. (a) Latencies to step onto the bridge. (b) Touching the handrail (light bars) and bridge (dark bars). Exploration of the distance between bridge and handrail by (c) shifting back and forth between the bridge and the handrail and (d) gesturing toward the handrail while standing at the bridge.
Note. Error bars denote standard errors.

exploration on the 16-cm middle location only, $t(22) = 3.85$, $p < .01$.

To gauge the distance between the bridge and handrail and decide whether and how their bodies could span the distance between the two means, infants shifted their bodies back and forth between the bridge and handrail while still on the starting platform (Figure 4c) and leaned their bodies or stretched out their arms toward the handrail when they were standing in front of the bridge (Figure 4d). ANOVAs on frequency of body shifts and gestures toward the handrail revealed main effects for bridge width and interactions between bridge width and bridge location (rows F and G, Table 1); the ANOVA on exploratory shifts also revealed a main effect for bridge location. Post hoc comparisons revealed that infants vacillated between the bridge and handrail more often on the 16-cm bridge than on the 36-cm bridge at both the middle and far locations, shifted more often at the middle and far locations than at the flush location on both bridge widths (all ps < .03), and gestured toward the handrail more often when the bridge was 16 cm than when it was 36 cm at the middle location, $t(22) = 4.03$, $p < .01$.

Individual Differences

On average, infants were 78.51 cm tall (range = 70.05–91.00 cm) and their mean arm span from fingertip to fingertip with arms outstretched was 81.69 cm (range = 76.20–88.45 cm). This means that the handrail fell at approximately elbow level and, in the far position, the handrail was beyond their reach unless they leaned nearly parallel to the ground. Infants' mean weight was 10.42 kg (range = 8.54–12.75 kg). Taller infants walked faster on baseline trials, $r(21) = -.51$, $p < .02$. Neither body dimensions nor days since walking onset were correlated with exploratory behaviors, attempts to cross the bridges, or success at crossing. However, infants' arm span was significantly correlated with handrail use. The longer their arms, the more likely they were to use the handrail, $r(23) = .42$, $p < .05$, and to carry out strategies for spanning the distance between the handrail and the bridge (leaning their bodies as they walked or walking with an arm outstretched to reach the handrail), $r(23) = .45$, $p = .03$.

Walking proficiency was related to performance on the bridges. The longer the distance between each footstep on baseline trials (an indication of mature gait), the shorter infants' latencies to step onto the bridge, $r(28) = -.46$, $p < .02$, the less likely they were to explore the distance between bridge and handrail, $r(28) = -.44$, $p < .02$, and the more likely they were to cross successfully, $r(28) = .47$, $p < .02$.

Handrail use and success were correlated with strategies for coping with the distance between the bridge and handrail. The more often infants gestured toward the handrail or shifted back and forth between the bridge and handrail on the starting platform, the more likely they were to use the handrail once on the bridge (Figure 1a; top panel Table 2). The more often infants leaned their bodies, stretched out their arms so that they could reach the handrail, turned their bodies sideways, or used both hands to hold onto the handrail when they were on the bridge, the more likely they were to cross successfully (bottom panel Table 2). For trials on the 16-cm bridge only, success was also related to whether infants used the handrail, $r(28) = .60$, $p < .01$.

Discussion

Means–Means–Ends Problem Solving

We examined infants' solutions to the localization problem of coordinating ''multiple and mobile frames of reference'' (Lockman, 2000, p. 140) in a whole-body, means–means–ends task. This work advanced previous studies of infants' problem solving in three ways. First, infants had to

Table 2
Correlations Between Infants' Exploration of Distance Strategies and Handrail Use After Embarking and Crossing Strategies and Success

Strategy type	Outcome measure	
	Use handrail	
Exploration of distance	*r*(*df*)	*p* value
Lean body or stretch arms toward handrail	.42(28)	< .03
Shift body between bridge and handrail	.41(28)	< .03
	Success	
Crossing strategy	*r*(*df*)	*p* value
Lean body	.55(28)	< .01
Walk with outstretched arms	.58(28)	< .01
Turn sideways on bridge	.71(28)	< .01
Use both hands to hold handrail	.69(28)	< .01

coordinate three key spatial relations on each trial—bridge and handrail, bridge and body, and handrail and body—rather than coordinate two frames of reference, such as object and surface or actor and tool (e.g., Bourgeois, Khawar, Neal, & Lockman, 2005). Second, infants had to monitor changes in spatial relations of the two means due to variations in bridge location. Third, with each step on the bridge, infants had to update their assessment of the spatial relations.

Sixteen-month-olds were active problem solvers. When infants attempted to cross narrow bridges, they juggled fitting their bodies onto the bridge, testing whether they needed a handrail to augment their balance, and orienting their bodies so that their upper extremities were securely on the handrail while their feet were firmly on the bridge. Infants viewed the bridge as a means for crossing the walkway, the handrail as a means for augmenting balance, and their own bodies as the link between the two. Failures were infrequent, suggesting that infants coordinated three simultaneously changing spatial relations. This finding is the first systematic demonstration of parallel coordination of multiple means in a problem-solving task in human infants.

Bridging the Gap: Understanding Spatial Relations

This experiment bridged the gap between research on spatial reasoning and studies of locomotor development. Typically, means–means–ends tasks require sequential implementation of means, such as using a knife to slice a lemon and then a reamer to squeeze out the juice. Alternatively, multiple means can be carried out in parallel, such as using salad servers to dole out a serving. Logically, infants would have to perceive a bridge as too narrow before considering whether a handrail was a viable means for augmenting balance. On wide bridges, infants ignore the handrail; they run straight across without touching the handrail (Berger & Adolph, 2003). However, once infants recognized a bridge as too narrow to serve as a sole means for crossing the precipice, they considered the spatial relations of the two means relative to each other and to themselves. Handrail and bridge-crossing strategies were highly sensitive to the spatial configuration of each condition. On most narrow bridge crossings, infants were already holding the rail as they stepped onto the bridge or grabbed onto it immediately after, indicating consideration of the two means in parallel, rather than in sequence, before going onto the bridge.

Previously (Berger et al., 2005), we postulated that implementing a means might lag behind recognizing a means because of a reported delay between the time toddlers choose the appropriate tool to solve a problem at about 21 months old and the time they actually use the tool to solve the problem at about 31 months old (Chen & Siegler, 2000). But this might not be true. Instead, success may result from the opportunity to devise clever, new solutions. Infants used their bodies to assess distance with the explicit purpose of determining whether the handrail and bridge in combination could be used as means to solve the problem. Infants devised new ways of using the handrail unobserved in previous bridge and handrail studies such as leaning forward while walking sideways (Figure 1b). Forcing infants to choose from a fixed set of behaviors determined by the experimenter and to use tools arranged inches from midline (e.g., Chen & Siegler, 2000; Smitsman & Cox, 2008) may artificially limit infants' ability to figure out the means to an end. In real life, tools may be at a great distance, and creativity is crucial for devising solutions to novel problems.

The suite of bridge–handrail studies showcases impressive problem solving in 16-month-old infants. Infants demonstrated knowledge about needing a suitable floor for crossing, about recruiting implements from the environment to enhance balance control, and about modifying typical locomotor strategies in response to ongoing challenges. The task for future research is to trace the developmental history beginning with cruising infants' first recognition that they can use a handrail as a means to support themselves to the sophisticated behaviors demonstrated by 16-month-olds as they solve means–means–ends problems.

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